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THE INFLUENCE OF FLY ASH AND PHOSPHOGYPSUM ON SELECTED SOIL TILTH PARAMETERS OF SOILS RECONSTRUCTED AFTER THE SURFACE MINING OF COAL.

BY

RICHARD M. LUSSIER

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

SOIL SCIENCE

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

SPRING, 1994

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled THE INFLUENCE OF FLY ASH AND PHOSPHOGYPSUM ON SELECTED SOIL TILTH PARAMETERS OF SOILS RECONSTRUCTED AFTER THE SURFACE MINING OF COAL submitted by RICHARD M. LUSSIER in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in SOIL SCIENCE.

D.S. Chanasyk

M.J. Dudas

John Hastie

Brian Kenyon

I.A. Campbell

D.J. Pluth

The earth was made so various that the mind of desultory man, studious of change and pleased with novelty, might be indulged.

William Cowper
The Task, 1780

Abstract

Phosphogypsum (PG) and fly ash (FA) are two industrial by-products presently being stockpiled in Alberta. Both have potential to improve soil structure. Use of surface mining in the extraction of coal from central Alberta and subsequent reclamation efforts using topsoil and subsoil from the mined areas has in some instances resulted in soils with poor tilth. Three research sites were established in June 1990 at the Highvale coal mine, 80 km west of Edmonton, Alberta to determine the effects of PG and FA on soil tilth. The three sites gave a range of sodicity levels, tilth characteristics, crusting potentials and trafficability. FA and PG were applied at rates of 6, 13, 26 and 53 Mg ha^{-1} and incorporated to a depth of 10 cm. Five replicates were used at each site. At all sites PG increased EC (electrical conductivity) and decreased SAR (sodium adsorption ratio) and pH. FA significantly increased soil pH at all sites when applied at the higher rates. Addition of FA at higher rates did not significantly increase EC nor did it significantly decrease SAR. Larger rates of FA addition would be needed in order to further decrease SAR in sodic soils. Soil surface strength (measured in situ), MOR (modulus of rupture) and dry and wet aggregate size distribution measurements were used to quantify the effects of PG and FA on soil tilth. Critical levels for soil surface strength were assumed to be 100 kPa and 50 % for change in aggregate size, calculated by the ratio: wet-sieved MWD:dry-sieved MWD. In order to achieve these levels, additions of PG at 26 Mg ha^{-1} would be required at the most sodic site (SAR of 6.9 at time of site establishment). For this site, addition of 53 Mg ha^{-1} FA would be needed. At a less sodic site, rates of addition of PG needed would only be 6 Mg ha^{-1} and addition of FA would be needed at a rate of 26 Mg ha^{-1}. The third site, on a naturally occurring soil, would not have needed any additions of PG or FA from a soil tilth point of view because results from the 0 Mg ha^{-1} rate were already below critical levels. Several environmental concerns must be addressed before PG or FA can routinely be used as soil amendments.

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Chapter 1. Introduction

The predominantly agricultural areas on the Canadian Prairies and the northern Great Plains of the U.S.A contain large coal reserves. The most common coal extraction technique in these areas is surface mining, which involves the removal of overburden (spoil) atop coal seams using large shovels, draglines or bucket-wheel excavators capable of handling massive amounts of material (Paone et al., 1978). Once the coal is removed the spoil is placed back into the mined area. The dominant method of reclamation of surface-mine spoils in western North America is the spreading of topsoil and/or subsoil onto contoured spoil, followed by revegetation (Merrill et al., 1980). Topsoil is stripped from the land and stockpiled in a premining process.

Manipulation of soil using heavy equipment drastically affects soil structure, especially if the soil already has properties which make it difficult to manage under normal conditions. Sodic and poorly structured soils are such problem soils. In the 1970s and early 1980s at the Highvale Coal Mine, approximately 80 km west of Edmonton, Alberta, areas which were overlain by these problem soils were mined. Manipulation of a Black Solodized Solonetz and a Dark Gray Luvisol resulted in the almost total destruction of any inherent soil structure, creating a compacted, structureless soil. In order to return these areas to their original agricultural potential, good soil tilth has to be restored. Tilth can be defined as: the physical condition of soil as relates to its ease of tillage, fitness as a seedbed, and its impedence to seedling emergence and root penetration (Hausenbuiller, 1985). Stabilizing the soil structure to decrease surface crusting and increase aggregate stability is the first step in restoring tilth.

In order to increase soil stability, soil dispersion must be decreased and flocculation increased. Dispersion leads to the breakdown of soil aggregates, the development of soil crusts, reduced water infiltration, high runoff and erosion, and restricted plant establishment and growth (Shainberg et al., 1989). Soil dispersion and swelling in smectitic soils is determined mainly by the presence of Na on the exchange

complex (Schofield and Samson, 1954). Replacement of Na on the exchange complex with Ca and an increase in the electrolyte concentration of the soil solution will increase flocculation of the clay platelets, resulting in a more stable soil structure. To provide both Ca for exchange with Na and a high enough electrolyte concentration in the soil solution, materials must be applied which are high in soluble Ca and which maintain a level of electrolytes to keep the soil flocculated. Two such materials are phosphogypsum and fly ash.

Phosphogypsum is a by-product from the production of phosphoric acid from rock phosphate (apatite). Phosphoric acid is in turn used in the manufacturing of phosphorus fertilizers. Worldwide production of phosphoric acid, estimated at 11 million Mg of P annually, results in approximately 125 million Mg of phosphogypsum, with only about 4 % of this being used in agriculture, in gypsum board and in cement industries (Alcordo and Rechcigl, 1993). The resulting stockpiling of phosphogypsum presents serious disposal problems. The accumulation of large phosphogypsum stockpiles creates a significant, and possibly negative environmental impact, unless it can be used beneficially.

Fly ash is a by-product of electricity produced by coal-fired generating plants used to generate electricity. In Canada, over 3 million Mg of fly ash is produced annually in Nova Scotia, New Brunswick, Ontario, Manitoba, Saskatchewan and Alberta (Joshi and Nagaraj, 1987). Approximately 10 to 20 % of fly ash has been used for partial replacement of cement in concrete, structural fill, back fill, embankment material, stabilization of soils and aggregates for pavements and *in situ* improvement of soils and sanitary landfills by lime-fly ash injection (Joshi and Nagaraj, 1987). The remainder is most commonly disposed of in the terrestrial environment (Warren and Dudas, 1984).

Both phosphogypsum and fly ash have the potential to improve soil structure and their use in the reclamation of surface mined and in the rehabilitation of naturally occurring problem soils may solve the problems encountered with disposal. Characteristics of fly ash and phosphogypsum produced in Alberta are specific to the raw materials and

processes used in their production. Much of the phosphogypsum research has centered on the reclamation of sodic soils, on decreasing soil erodibility and on increasing water infiltration. What little research that has been done with phosphogypsum in the reclamation of surface mined areas has been associated with sodic spoil and not with the tilth characteristics of the topsoil. Much research has been carried out on the utilization of FA in the reclamation of surface mined land. Chang (1977) found that even small amounts of FA decreased the modulus of rupture (MOR) of soils (index of soil crust strength) in five California soils. Greenhouse experiments using fly ash-soil mixtures (Lutwick et al., 1981) showed that there were no changes in MOR when fly ash was applied to two Solodized Solonetz soils.

The use of phosphogypsum and fly ash as soil amendments has not been widely accepted due to certain environmental concerns. Previous research has found that acidity, F^-, SO_4^{2-}, certain trace elements and certain radionuclides may be elevated in phosphogypsum and have the potential to be mobile in the environment. The largest concern in the use of phosphogypsum as a soil amendment is not from the levels of radionuclides present, but from the risk of elevated indoor radon levels if the phosphogypsum-amended land is later converted to residential use (Rutherford et al., in press). As a result, the U.S. E.P.A has ruled that no phosphogypsum may be used as a soil amendment if its radon (in the form of Ra-226) content exceeds 370 Bq kg^{-1}.

Although fly ash has been found to improve soil physical properties, its addition to soil has also resulted in both beneficial and detrimental effects on crop yield and growth. The most often cited cause of detrimental effects has been boron phytotoxicity; As, Mo and Se have also been found in concentrations potentially toxic to grazing animals as a result of fly ash additions to soil (El-Mogazi et al. 1988). Most of the environmental concerns regarding the use of phosphogypsum and fly ash as soil amendments have been raised when very large amounts of the two products are applied; usage in smaller amounts may prove to be insignificant in terms of any detrimental effects to the environment.

Little field research involving addition of PG or FA in the reclamation of soils reconstructed after surface mining has been conducted in Alberta, with even less of this research focusing on soil physical properties. Luvisol, Solonetz and Solodized Solonetz soils are very common in Alberta where surface mining is practiced, thus creating a need to better understand the implications of surface mining and subsequent reclamation methods of these soils. A field study was initiated in the summer of 1990 at the Highvale coal mine in which two industrial by-products, phosphogypsum and fly ash, were applied at varied rates accross three sites. The objective of this study was to determine the effects, either beneficial or detrimental, of phosphogypsum and fly ash on selected soil tilth parameters of soils reconstructed after surface mining of coal and naturally occurring soils.

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Chapter 2. Site Characterization, Experiment Design, and Methodology

2.1 Site characteristics

Three field research sites were chosen at the Highvale Mine, approximately 80 km west of Edmonton, Alberta (Figure 2.3) to give a range of tilth characteristics, crusting potential and trafficability. The following is a description of soil and reclamation history for each of the sites. Soil survey data in this chapter were obtained from TransAlta Utilities soil surveys.

Site 1.

Site 1 is located in Pit 02 of the Highvale Mine, south of the Sundance Generating Plant Cooling Pond. Before being strip mined in the late 1970s, the majority of the soils surrounding the present Site 1 location were classified as Black Solodized Solonetz (Wabamun-1 map unit). Profile and chemical descriptions of the Wabamun-1 map unit can be found in Table 2.1. The premining process included stripping, and stockpiling of the various soil layers. The 0-20 cm layer (Ap and Ae horizons combined) was stripped and stockpiled, the 20-55 cm layer (mostly Bnt) was also stripped and stockpiled separately from the 0-20 cm layer. After mining, spoil was returned to the mined area, leveled, contoured and the previously stripped soil layers were replaced in their proper sequence. The area surrounding Site 1 was reconstructed during 1982-83. During the 8-9 years preceding the establishment of the research site, very few, if any, crops were grown due to the poor tilth and trafficability of the area. The reclaimed area underwent a deep tillage operation using a deep ripping implement shortly after being reclaimed. At the time of site selection, the presence of large clods at the soil surface, many in excess of 15 cm in diameter, and the poor trafficability of the site were prime reasons for this site being chosen. Before the application of PG and FA at Site 1, random soil samples were taken to a depth of 55 cm (0-10, 10-25, 25-40 and 40-55 cm intervals) in June of 1990 from within the plot area (30 x 55 m) in order to obtain baseline values for chemical and physical characteristics (Table 2.2a). Compared to the Wabamun-1

map unit (Table 2.1) the minesoil had both higher Na and clay at similar depth intervals. Increased clay in the minesoil is most likely due to mixing of the salvaged soil horizons, resulting in a higher clay content throughout the 0-55 cm minesoil profile. Increases in sodium may also be due to the mixing of horizons, or the diffusion of Na from the spoil into the overlying soil (McAllister Env. Serv., 1985). Sodium adsorption ratio (SAR) of the Wabamun Solodized Solonetz range from 5.1 in the Ap to 10.0 in the Ae, while those of the Site 1 minesoil range from 6.9 in the 0-10 cm layer to 12.0 in the 40-55 cm depth interval. Total soil carbon values range from 3.4% in the 40-55 cm layer to 1.7% in the 0-10 cm layer. Total carbon values may not represent the true levels of organic matter due to the presence of coal in the soil profile. Higher pH in the minesoil (7.4 at 0-10 cm) compared to the Wabamun-1 soil (4.7 at 0-10 cm) may be due to the resalinization of the profile or the mixing in of some of the IICsk horizon during reclamation.

Site 2

Site 2 is located in Pit 03 of the Highvale Mine, west of the Sundance Generating Plant. The majority of soils surrounding Site 2, before mining, were classified as Dark Gray Luvisols (Uncas-1 map unit). Chemical and profile descriptions of the Uncas-1 soil can be found in Table 2.3. The area surrounding Site 2 was mined in the early to mid-1980s and reclaimed in 1986. The premine process in this area involved the harvesting and stockpiling of the 0-20 cm Ap and Ap_2 horizons and (separately) the next 150 cm of subsoil. The layers were replaced in their original order once spoil was spread and contoured. Large clods at the soil surface and poor seedbed quality at the time of site selection indicated the poor tilth characteristics of this site.

Soil samples were taken in June 1990 from within the plot area (30 x 55 m) in order to obtain baseline values for chemical and physical characteristics (Table 2.2b). Total soil carbon ranged from 2.6% at 0-10 cm to 2.8% at 40-55 cm. These values may not represent true levels of organic matter due the presence of coal in the soil profile. Little mixing of horizons

has occurred during the reclamation process due to the relatively similar clay contents at similar depth intervals (Table 2.2b and 2.3). Sodium levels however, are higher in the Site 2 minesoil than in the Uncas-1 soil. This may be due to upward diffusion of Na from underlying sodic spoils which may have been mixed in with the original non-sodic parent materials or the mixing of other Na-affected soils or spoils with the Uncas-1 Dark Gray Luvisol.

Site 3

Site 3 is located west of the Sundance Generating Plant and east of Site 2. The legal land location of Site 3 is SW 29-52-5-W5. No mining has taken place at this site. The soil around Site 3 is classified as a Gleyed Dark Gray Luvisol (Fawcett-1 map unit) which was developed on non-sodic slopewash material (Table 2.4). Although tilth was better at Site 3 than at Sites 1 and 2 at the time of site selection, this site was chosen because it was a naturally formed soil which, being of the Luvisolic Order, is prone to surface crusting due to the mixing in of the Ae horizon into the Ap through cultivation.

Before the application of PG and FA at Site 3, random samples were taken in June 1990 from within the plot area (30 x 55 m) in order to obtain baseline values of the site's chemical and physical characteristics (Table 2.2c). Site 3 has relatively low Na (soluble and exchangeable) compared to Sites 1 and 2. Sand content is approximately 10% higher (absolute) at this site than at the other two sites. Total soil carbon may not represent true levels of organic matter due the presence of coal in the soil profile (2.3% at 0-10 cm and 1.6% at 40-55 cm).

Summary

These three sites were chosen on the basis of their poor tilth characteristics, namely cloddiness, crusting potential and poor trafficability. These characteristics were observed visually; no quantitative measurements were made. It appears that, chemically, if not physically, there is a gradation in the severity of sodicity and quality of tilth among sites. The

most severe sodicity and poorest tilth occurs at Site 1 and the least affected in terms of sodicity and poor tilth is at Site 3. Sodicity and tilth characteristics at Site 2 are intermediate to those at Sites 1 and 3.

2.2 Experiment design

Sites 1, 2 and 3 were established on June 18, 15 and 8, 1990, respectively. Phosphogypsum and fly ash were applied manually, at rates of 0, 6, 13, 26 and 53 Mg ha^{-1}, and incorporated to a depth of 10 cm, using a tractor-mounted rotary tiller, immediately after application. The PG and FA were weighed with a spring-loaded scale to ensure that the proper amount of amendment was added to each plot. Practicality in application and a review of previous work involving PG and FA were considered when deciding what rates of PG and FA to apply. The highest rate of 53 Mg ha^{-1} is equivalent to 5% of the soil mass at the 0-10 cm depth (assuming a soil bulk density of 1.05 Mg m^{-3}). The PG used was obtained from Esso Chemicals Canada in Redwater, Alberta. The Ca content of a PG-water paste extract was 24 mmol L^{-1} and pH of a 1:1 PG:water solution was 2.4. Ca content of the FA-water paste extract was 12 mmol L^{-1} and the pH of a 1:1 FA:water solution was 12.3. The unweathered FA was obtained from the Sundance Generating Plant at Highvale. Plots were laid out in a randomized complete block form. Each block contains PG and FA each applied at the four previously mentioned rates and the 0 Mg ha^{-1} rate, for a total of nine treatments within a block. Each site had five blocks. Each individual treatment (plot) within a block had dimensions of 5 x 5 m, with a 1 m wide buffer strip separating each plot. Figure 2.2 shows the layout of the plots.

Plots were kept free of any plant growth throughout the experiment with the use of tillage and herbicide applications. All plots were rotary tilled in August 1990 and herbicide (Round-up™) applied in September 1990 to kill weeds. In order to remove the soil crust formed during winter 1990-91, the sites were tilled on June 5, 1991 and herbicides were applied in July 1991 to suppress weed growth.

Precipitation data were gathered during the study period in order to determine how much rainfall contacted the soil surface for soil crust development and how much water was available for the dissolution of PG and FA in the soil. Precipitation was measured at a meteorological station situated approximately 100 m from Site 1. Due to the close proximity of the three sites, rainfall was assumed to be the same at all sites. Total rainfall from the time of plot establishment on June 18, 1990 to October 31, 1990 was 209 mm, with over half of this amount falling in a 3-day period during the first week of July. The amount of rainfall from April 26, 1991 to the time of bulk soil sampling during the first week of October 1991 was 313 mm. The total amount of rainfall over the 16-month period, from plot establishment to soil sampling in October 1991 was 522 mm. This rainfall data does not include snowfall data nor rainfall data from October 31, 1990 to April 26, 1991. The rainfall distribution for the two summers (1990 and 1991) in which the plots were established and monitored is given in Figures 2.1a and b. Using the mean rainfall from 1951 to 1980 at the Stony Plain meteorological station, located approximately 30 km to the northeast of the research site, mean rainfall from the time of plot establishment on June 18, 1990 to October 31, 1990 is 323 mm. The mean rainfall from April 26, 1991 to the time of soil sampling during the first week of October 1991 is 348 mm. The total mean rainfall over the 16 month period is 694 mm and the total mean snowfall is 133 mm.

2.3 Methodology

Soil chemical analyses

Samples for chemical analysis were taken during the first week of October 1991, approximately 16 months after plot establishment. Four samples, at depth intervals of 0-10, 10-25, 25-40, and 40-55 cm were taken randomly from each plot, with the four samples from similar depth intervals being combined to form a composite sample. Soil samples were obtained with a truck-mounted core sampler using a 5-cm coring tube. Samples were air dried and ground to pass a 2-mm round-holed sieve.

A 1:2 soil:water suspension was used to determine soil pH using a Model 630 Fisher Accumet pH meter (Fisher Scientific Co., U.S.A.). Extracts from saturated soil pastes, following McKeague (1978), were analyzed for soluble Ca, Mg, and Na using a Model 530 Atomic Absorption Spectrophotometer (Perkin Elmer, Norwalk, Connecticut, U.S.A.). Electrical conductivity of paste extracts was measured using a Model 31 conductivity bridge (Yellow Springs Instrument Co., Inc., Ohio, U.S.A.) following McKeague (1978). In the chemical analyses of the PG-amended soils, the 0-10 cm depth interval from all five blocks, and those samples from the first three blocks in the 10-25, 25-40 and 40-55 cm depth intervals, from each of the three sites, were analyzed. For the FA-amended soils, the 0-10 cm depth interval from all five blocks, and samples from the first three blocks in the 10-25 cm depth interval were analyzed

Surface strength determinations

In situ surface strength (ISS) measurements were taken using an adapted cone penetrometer. Rather than using a cone-shaped probe in order to measure penetration strength of the crust, a flat-bottomed cylindrical probe (20-mm diameter) was attached to a hand-held penetrometer (Soil Test, Inc. Cone Penetrometer model #CN-973, Evanston, Illinois, U.S.A.). ISS readings were taken by pushing the probe downward until the probe broke through the surface crust. At breaking point, the gauge was read and the measurement recorded. Five measurements were taken over a distance of 1.0 m in each plot; thus, each ISS value in Figure 3.7 is an average of 25 readings. Soil samples (approximately 50 g) for determination of gravimetric moisture content, 0-2.5 cm depth, were taken near the surface strength measurement area in each plot. Samples were weighed, oven-dried at 105^{o}C for 24 hours, reweighed and the moisture content determined on a mass basis. Readings were taken on the following dates: Aug 19, Sept. 3 and Sept. 25, 1991 at Site 1; Sept. 3 and Sept. 25, 1991 at Site 2; Sept. 10 and Sept. 25, 1991 at Site 3. Modulus of rupture tests were carried out on the surface samples (0-10 cm) obtained in October, 1991. The modulus of rupture procedure followed was that of Reeve (1965).

Size distribution and stability of aggregates

Samples for determination of dry aggregate size distribution were taken on August 7, 1991 from the 0-10 cm depth interval. One sample was taken from each plot using a rectangular shovel, for a total of five samples for each treatment at each site. Samples were air-dried and shaken through a nest of sieves composed of the following size openings: 25, 12.5, 9.5, 6.3, 4, 2, 1, 0.5, 0.25 and 0.125 mm and a pan to catch aggregates <0.125 mm. Soil from each size range was weighed and aggregate size distributions (% of sample) and mean weight diameters (MWD) were calculated using equation (1). MWD is equal to the sum of products of the mean diameter x_i of each size fraction and the proportion of the total sample weight w_i occuring in the corresponding size fraction, where the summation is carried out over all n size fractions, including the one that passes through the finest sieve: (Van Bavel, 1949; Youker and McGuiness, 1956; Kemper and Chepil, 1965):

$$\text{MWD} = \Sigma\, x_i\, w_i \quad (i=1 \text{ to } n) \tag{1}$$

Samples for wet aggregate stability analyses were obtained during the first week of October 1991, at the same time as samples for chemical analysis were being taken. Four samples from within each plot were taken from the 0-10 cm surface layer using a rectangular shovel. The four samples were combined to form a composite sample for each plot, resulting in five composite samples for each site. Samples were air-dried (3-4% mass moisture basis) before analysis took place. Samples were passed through a 9.5-mm sieve, with some of the larger aggregates having to be gently pushed through with a rubber stopper. Triplicate 35-g sub-samples were wet-sieved (modified from Kemper and Chepil, 1965) through a nest of sieves for 10 minutes after letting the soil moisten by direct immersion for 10 minutes on the top sieve. Distilled water, to simulate rainwater, at room temperature (22-23 ^{o}C) was used for wet-sieving in a Yoder-type apparatus. Sieves oscillated 30 times per minute through an amplitude of 3.75 cm. The nest of graduated sieves had equivalent diameters of 4, 2, 1, 0.5,

0.25 and 0.125 mm. The soil mass retained on each sieve was oven dried (105 ^{o}C) and weighed. Size distribution of the retained aggregates and MWDs were calculated.

Statistical analyses

Results were subjected to analysis of variance using ANOVA procedure of the SAS statistical package (SAS Institute, Inc., 1985). Data were analyzed as a randomized complete block. Duncan's Multiple Range (DMR) tests ($P< 0.05$) were performed for comparing means of treatment effects which showed significant F-values in the analysis of variance ($P> F< 0.10$). In some cases some parameters were plotted against each other and simple linear correlations were carried out using CA-Cricket GraphTM software (Computer Assiciates International, Inc., San Diego, CA).

2.4 References

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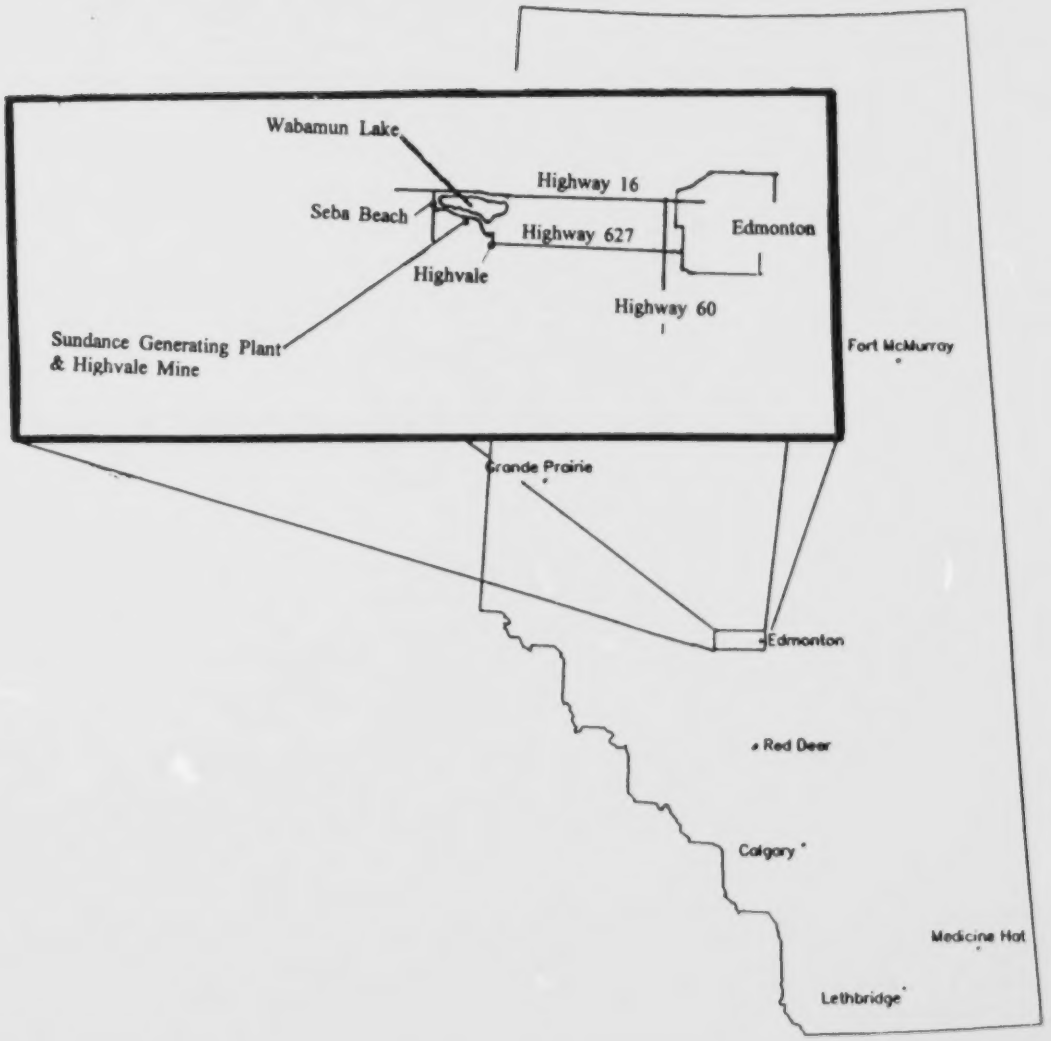

Figure 2.3 Location of the TransAlta Utilities Sundance Generating Plant and Highvale Coal Mine.

Table 2.1

Description of map unit Wabamun-1

(Site description)

Dominant Soil:	Black Solodized Solonetz
Parent Material:	Lacustrine veneer over sodic residual
Landform:	Glacio-lacustrine veneer
Slopes:	Nearly level - very gentle (1-3%)
Drainage:	Imperfect
Surface Stoniness:	Non-stony
Roots:	120 cm

Profile Description

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence
Ap	0-10	gray	loam-clay loam	moderate fine to medium subangular blocky	slightly hard
Ae	10-20	light gray	silt loam	moderate to strong medium platy	hard
Bnt	20-43	brown to dark brown	clay	strong medium columnar	very hard
IICsk	43-120	dark gray	clay to heavy clay	massive	hard

Soil properties

Horizon	Sand (%)	Silt (%)	Clay (%)	pH	Org C (%)	EC (dS/m)	CEC (me/100 g)	SAR	ESP	Satur'n (%)
Ap	18	51	31	4.7	3.9	0.95	37.0	5.1	2.7	54
Ae	18	56	26	4.2	0.96	0.68	17.8	10.0	4.3	26
Bnt	11	44	45	4.7	0.88	0.61	32.2	7.9	7.6	38
IICsk	27	16	57	3.9	0.74	1.10	42.2	9.0	5.6	81

Table 2.2a Baseline soil properties of Site 1.

Depth (cm)	Sand %	Silt %	Clay %	pH (water)	% Total Carbon	EC (dS m^{-1})	Soluble cations (mmol L^{-1}) Ca	Mg	Na	K	ESR	SAR
0-10	14	45	41	7.4	1.6	1.5	2.1	0.87	12	0.24	0.14	6.9
10-25	14	43	43	7.7	1.4	2.6	3.7	1.3	20	0.19	0.18	9.1
25-40	12	36	52	7.2	1.1	4.1	6.8	2.2	32	0.29	0.23	11
40-55	12	37	51	7.1	3.9	3.4	5.4	2.0	33	0.23	0.23	12

Table 2.2b Baseline soil properties of Site 2.

Depth (cm)	Sand %	Silt %	Clay %	pH (water)	% Total Carbon	EC (dS m^{-1})	Soluble cations (mmol L^{-1}) Ca	Mg	Na	K	ESR	SAR
0-10	17	46	37	6.2	2.6	1.7	3.6	1.8	6.7	0.26	0.07	2.9
10-25	18	43	39	6.7	2.5	1.3	2.8	1.3	7.7	0.14	0.08	3.8
25-40	16	34	50	7.4	2.4	2.2	4.2	1.7	11	0.21	0.08	4.4
40-55	17	33	50	7.3	2.8	1.9	4.2	1.8	12	0.25	0.09	4.7

Table 2.2c Baseline soil properties of Site 3.

Depth (cm)	Sand %	Silt %	Clay %	pH (water)	% Total Carbon	EC (dS m^{-1})	Soluble cations (mmol L^{-1}) Ca	Mg	Na	K	ESR	SAR
0-10	26	49	25	5.7	2.3	1.8	6.0	2.6	1.4	0.46	0.03	0.48
10-25	25	47	28	5.9	2.0	0.66	2.0	1.0	1.4	0.13	0.03	0.80
25-40	24	28	48	5.6	1.4	0.40	0.98	0.50	1.3	0.09	0.03	1.0
40-55	24	26	50	5.5	1.6	0.24	0.95	0.22	1.07	0.05	0.03	0.99

Table 2.3

Description of map unit Uncas-1
(Site description)

Dominant Soil:	Dark Gray Luvisol
Parent Material:	Till derived from mudstone (non sodic)
Landform:	Morainal
Slopes:	Level - very gentle slopes (0-2%)
Drainage:	Moderately well drained
Surface Stoniness:	Non-stony

Profile Description

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence
Ap	0-13	very dark grayish brown	silt loam	moderate medium granular	friable
Ap_2	13-20	dark grayish brown	silt loam	weak coarse sub angular blocky	friable
Aegj	20-26	grayish brown	silt loam	moderate fine platy	friable
AB	26-35		silty clay loam	weak coarse platy - sub-angular blocky	friable - firm
Bt	35-60	black	clay	moderate medium prismatic to strong fine angular blocky	firm
BC	60-65		clay - clay loam		firm
C	65-98+	very dark gray	clay	massive	very firm

Soil Properties

Horizon	Sand (%)	Silt (%)	Clay (%)	pH	Org C (%)	EC (dS/m)	CEC (me/100 g)	SAR	ESP	Satur'n (%)
Bt	21	23	56	6.7	N/A	0.13	N/A	1.26	N/A	64.7
C	24	22	54	6.4	N/A	0.12	N/A	1.13	N/A	64.9

Table 2.4

Description of map unit Fawcett-1
(Site Description)

Location:	Site 3, SW 29-52-5-W5
Dominant Soil:	Gleyed Dark Gray Luvisol
Parent Material:	Slopewash material (non sodic)
Landform:	Colluvial slope
Slopes:	Gentle (5-8%)
Drainage:	Imperfect
Surface Stoniness:	Non-stony
Roots:	80 cm

Profile Description

Horizon	Depth (cm)	Colour	Texture	Structure	Consistence
Ap	0-17	very dark gray	clay loam - silty clay loam	weak coarse angular blocky	friable
Btgj	17-32	dark grayish brown	clay loam	moderate fine subangular block	friable
BCgj	32-47	light brownish gray	loam	strong medium, pseudo-platy	firm
Cgj	47-82	grayish brown	loam	strong medium pseudo-platy	firm
Cgj_2	82-180	brown - dark brown	loam - clay loam	strong medium pseudo-platy	firm

Soil Properties

Horizon	Sand (%)	Silt (%)	Clay (%)	pH	Org C (%)	EC (dS/m)	CEC (me/100 g)	SAR	ESP	Satur'n (%)
Ap	21	44	35	6.4	5.4	0.28	33	0.2	0.6	52.9
Btgj	26	36	38	6.5	-	0.11	N/A	0.4	N/A	40.8
BCgj	42	37	21	6.7	-	0.12	N/A	0.4	N/A	33.4
Cgj_2	39	34	27	7.0	-	0.17	N/A	0.8	N/A	36.8

Site 1 North

PG 13	PG 6	0	PG26	FA 26	PG 53	FA 53	FA13	FA 6
FA 13	0	FA 53	FA 6	PG 13	PG 26	PG 6	FA 26	PG 53
PG 26	FA 13	PG 13	FA 53	0	FA 26	FA 6	PG 53	PG 6
FA 53	0	FA 26	FA 6	PG 26	PG 53	PG 6	FA 13	PG 13
PG 53	FA 13	PG 26	PG 6	FA 6	PG 13	FA 26	0	FA 53

South

Site 2 East

FA 6	PG 53	PG 6	0	FA 13	PG 26	FA 26	PG 13	FA 53
0	PG 6	FA 53	FA 6	PG 26	PG 53	PG 13	FA 13	FA 26
PG 53	PG 13	FA 6	PG 26	PG 6	FA 26	FA 13	FA 53	0
PG 26	FA 53	PG 53	0	PG 13	FA 6	PG 6	FA 13	FA 26
FA 6	FA 13	PG 13	PG 26	PG 6	0	PG 53	FA 26	FA 53

West

Site 3 East

PG 26	FA 13	PG 13	FA 53	FA 6	FA 26	PG 6	0	PG 53
FA 6	PG 53	0	FA 13	FA 53	PG 26	FA 26	PG 6	PG 13
PG 53	FA 53	PG 13	FA 26	0	PG 6	PG 26	FA 13	FA 6
PG 26	0	FA 53	PG 53	FA 6	FA 26	PG 13	PG 6	FA 13
PG 53	FA 13	PG 13	PG 6	PG 26	FA 53	0	FA 26	FA 6

West

Figure 2.1. Plot layout. PG=phosphogypsum, FA=fly ash; the numbers following the PG or FA designation signify the rate at which the amendment was applied in Mg ha^{-1}; 0= nothing applied.

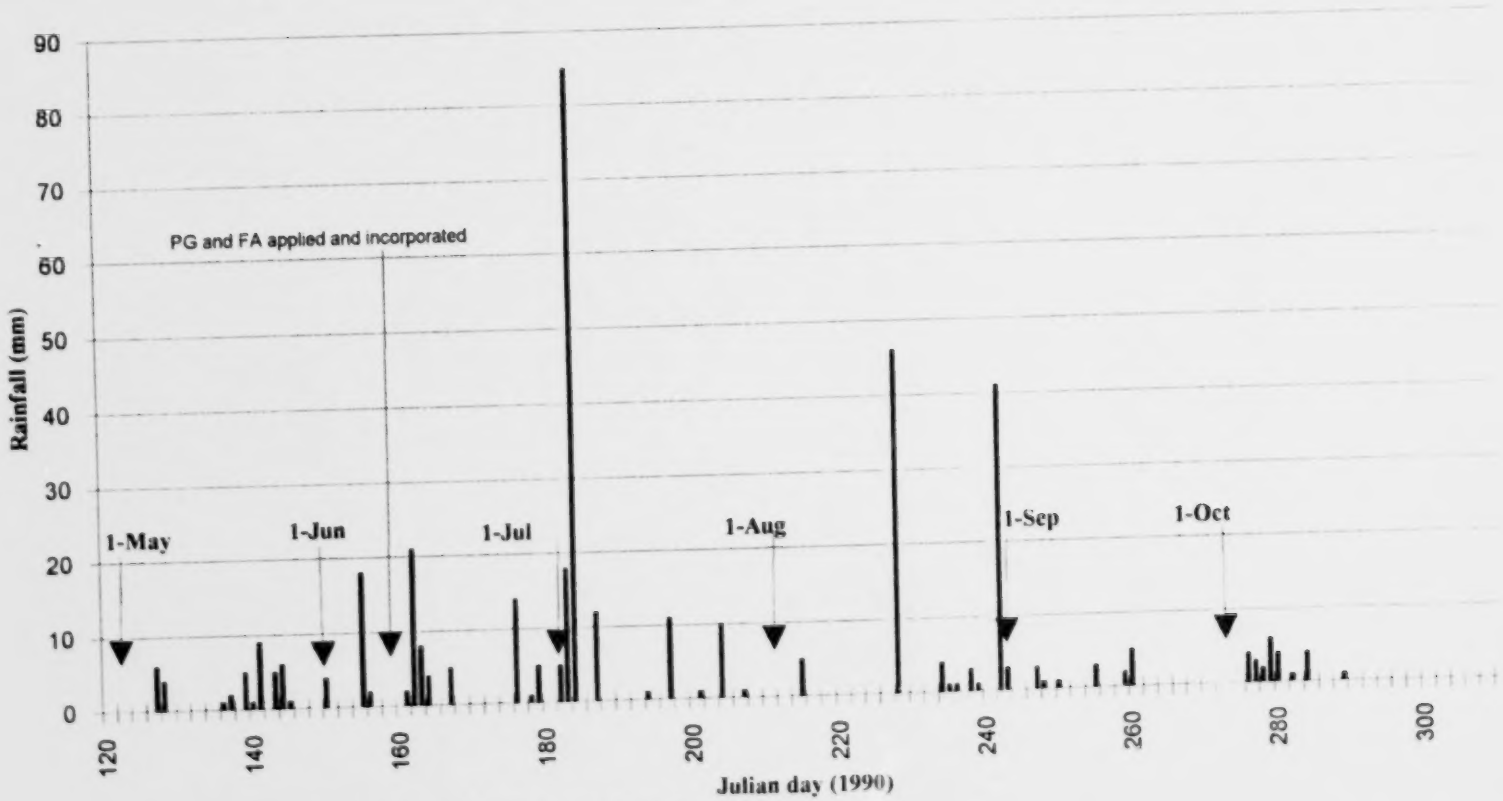

Figure 2.2a. Rainfall data at the Highvale Mine for 1990.

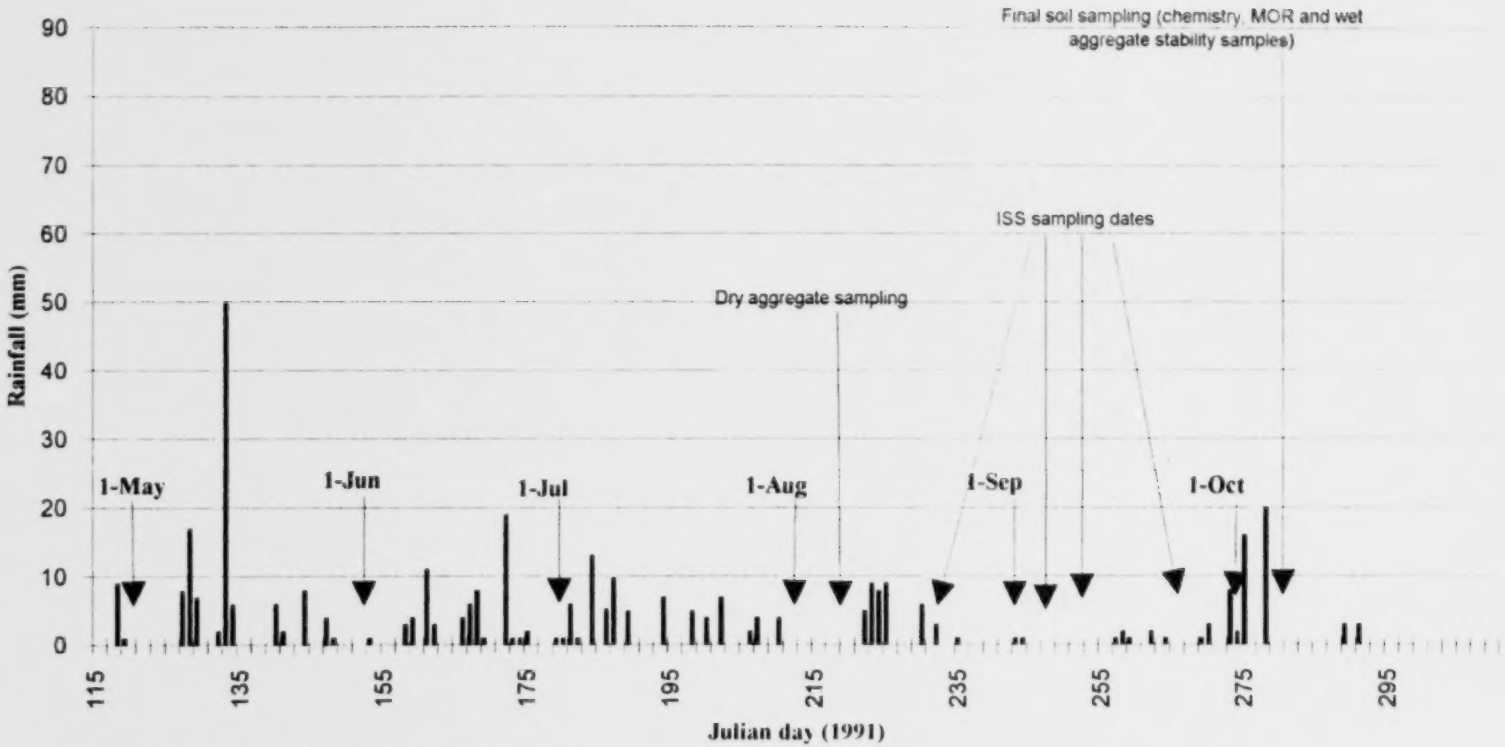

Figure 2.2b. Rainfall data at the Highvale Mine for 1991.

Chapter 3

3.1 Chemical characteristics of phosphogypsum-amended soil.

3.1.1 Introduction

The deleterious effects of Na and electrolyte concentration of percolating solutions on soil dispersion have been well documented (Quirk and Schofield, 1955; McNeal et al., 1968). However, the critical level of exchangeable Na that separates dispersive (sodic) soils from non-dispersive soils is not clear (Shainberg et al., 1989). An exchangeable sodium percentage (ESP) of 15 as the boundary between sodic and non-sodic soils was suggested by the U.S. Salinity Laboratory Staff (1954) with soils of higher ESP being dispersive and physically breaking down when wetted. A subsequent modification took into account the influence of soil texture with the critical ESP being 10 for fine textured soil and 20 for coarse textured soil (Bernstein, 1974). Continuous and rapid reductions in hydraulic conductivity as ESP increased above zero were measured in Australian soils (McIntyre, 1979), resulting in a proposed ESP of 5 as the threshhold value between sodic and non-sodic soils. Considering the latter as the critical level of exchangeable Na for separation of sodic and nonsodic soils, both Sites 1 and 2 would be considered sodic, with exchangeable sodium levels at Site 3 approaching the ESP threshold value of 5.

Permeability of a soil to water depends on both ESP and electrolyte concentration of the percolating solution, decreasing with increasing ESP and decreasing electrolyte concentration (Quirk and Schofield, 1955; McNeal et al., 1968). Soil permeability can be maintained at fairly high ESP levels provided that the electrolyte concentration of the infiltrating water is above a certain threshold level (Quirk and Schofield, 1955). However, when water with very low electrolyte levels is used (e.g. rain water), an ESP as low as 5 can cause a significant reduction in the permability of soils (McIntyre, 1979).

Reclamation of a sodic soil involves the replacement of Na with Ca, which can be supplied by gypsum, while maintaining the electrolyte concentration of the percolating water above a certain threshold level. This chemical reclamation process would involve,

simultaneously, mineral dissolution, cation exchange, and solute and water movement (Oster and Frenkel, 1980). More simply put, gypsum dissolves to provide, firstly, a level of electrolyte in the soil solution which maintains sufficient permeability to allow water entry into and through the soil profile and at the same time, provides Ca for exchange with Na (Loveday, 1984).

Depending on the rate of water application and gypsum dissolution, sufficient electrolyte concentration can be achieved to prevent dispersion and associated reductions in soil water permeability (Shainberg et al., 1989). Electrolyte concentrations, with a gypsum saturated soil, can potentially range from 18 to 135 mmol L^{-1} as the exchangeable Na fraction ranges from 0.10 to 0.50 (Oster and Frenkel, 1980). Actual electrolyte concentrations in gypsum saturated soils can range from near saturation (15 mmol L^{-1}; Dutt et al., 1972) to half saturation (6-8 mmol L^{-1}; Chaudhry and Warkentin, 1968). Factors affecting gypsum dissolution include: type of gypsum (Zarubina, 1979; Keren and Shainberg, 1981), particle size, hence surface area (Keren and Shainberg, 1981; Chawla and Abrol, 1982), and the presence of soluble salts in the soil solution (Shainberg et al., 1989). Zarubina (1979) and Keren and Shainberg (1981) demonstrated that phosphogypsum was more readily soluble than mined gypsum and calcium carbonate. Keren and Shainberg (1981) also demonstrated that larger particle sizes of phosphogysum dissolved more slowly than smaller particle sizes and that phosphogypsum dissolved more rapidly and resulted in higher equilibrium concentrations in increasing concentrations of NaCl solution. In saline soils, overall dissolution of gypsum is promoted by the exchange of Ca for other exchangeable ions, which may have a limited effect on raising equilibrium Ca levels by releasing diverse ions into soil solution (Shainberg et al., 1989). The diverse ion effect increases solubility of gypsum above that in pure water because of both ionic strength effects and ion pairing (Nakayama, 1971).

The amount of gypsum required for the reclamation of a sodic soil is dependent on the depth of soil to be reclaimed, the initial amount of exchangeable Na, and the final ESP

being sought (U.S. Salinity Laboratory Staff, 1954). The rate at which Ca exchanges for adsorbed Na varies with ESP, with much higher exchange rates occurring at greater ESP as studied by Chaudhry and Warkentin (1968), where 90% of exchangeable Na was removed from Wetaskiwin solonetzic soil by the first symmetry (in terms of Na) amount of Ca (equivalent to 4.2 meq L^{-1} of gypsum) using a half-saturated solution of gypsum (15.1 meq L^{-1}). Significant replacement of Mg began only after Na was removed. Application of up to 18 Mg ha^{-1} gypsum resulted in dramatic increases in soil hydraulic conductivity when soil ESP was less than 20, but results were not as consistent when ESP was 20-25, and depended upon the actual solubility of gypsum in the field (Graveland and Toogood, 1963).

Field studies in the reclamation of sodium-affected soils have shown positive effects of gypsum application (Mann et al., 1982; McIntyre et al, 1982; McAllister Env. Services, 1985). A gypsum application of 10 Mg ha^{-1} reduced the ESP of a silty clay soil from 15 to 7 in the 0-25 cm soil layer and from 30 to 19 in the 25-50 cm layer and also increased the outflow of subsurface drains by 40% (Mann et al., 1982). In a ponding experiment on a brown sodic clay, McIntyre (1982) observed that without gypsum, 276 mm of water infiltrated in 379 days, wetting the profile to 2.1 m and that with 10 Mg ha^{-1} of gypsum, 605 mm infiltrated in 145 days while decreasing the SAR in the 20-30 cm depth interval from 16.6 to 5.5. Seven years after application of gypsum (22.4 Mg ha^{-1}) on soils reconstructed on saline-sodic minespoil at the Highvale Mine, a decrease in SAR values, in both the soil and underlying spoil, and the downward movement of Ca and Mg ions released by the surface-applied gypsum through 90 cm of a sandy loam and a clay cover soil was observed (McAllister Env. Services, 1985).

Objectives of this study were to (1) determine the effect of various rates of PG application on the soil solution chemistry, with depth, of natural soils or soils reclaimed after coal strip mining and (2) to determine which rate of PG application is most beneficial in the improvement of soil tilth.

3.1.2 Materials and Methods

Please refer to Section 2.3.

3.1.3 Results and Discussion

3.1.3.i Soluble cations in soil paste extracts

At Site 1, soluble Ca in the 0-10 cm depth interval increased from 1.6 mmol L^{-1} in the 0 Mg ha^{-1} treatment to 6.0 mmol L^{-1} in the 6 Mg ha^{-1} PG treatment (Table 3.1). Addition of PG beyond 13 Mg ha^{-1} had no further significant effect on the amount of soluble Ca in the 0-10 cm surface layer, with concentrations of 12, 14 and 14 mmol L^{-1} present in the 13, 26 and 53 Mg ha^{-1} PG treatments, respectively. Although soluble Ca increased in the lower depth intervals, increases were not significant.

Analysis of saturated soil paste extracts of the samples obtained from Site 2 showed some downward movement of Ca, Mg, and Na into the 10-25 cm depth interval. All rates of PG increased soluble Ca significantly in the 0-10 cm layer, with no significant difference among the 6, 13, 26 and 53 Mg ha^{-1}application rates (Table 3.1). Soluble Ca increased from 4.4 mmol L^{-1} in the 0 Mg ha^{-1} rate to 13, 15, 15 and 16 mmol L^{-1} for the 6, 13, 26 and 53 Mg ha^{-1} PG application rates, respectively. There was a significant increase in soluble Ca in the 10-25 cm depth interval at the 53 Mg ha^{-1} application rate. Increases in soluble Ca at the lower rates of PG application in the 10-25 cm layer were observed, but they were not significant. Increases in soluble Ca, although not statistically significant, were also observed in the 25-40 and 40-55 cm depth intervals with increased rates of PG application.

Higher levels of soluble Ca were observed at lower depth intervals at Site 3 when compared to Site 2. Levels of soluble Ca in the 0-10 or 10-25 cm depth intervals increased significantly at all rates of PG application with no significant differences occurring among rates (Tables 3.2 and 3.3). Concentrations of soluble Ca in the 0-10 cm layer increased from 6.1 mmol L^{-1} in the 0 Mg ha^{-1} rate to a high of 19 mmol L^{-1} at the 53 Mg ha^{-1} application rate. For the 10-25 cm depth interval, the concentration of Ca in

the soil solution increased from 1.6 mmol L^{-1} in the 0 Mg ha^{-1} rate to 9.9 mmol L^{-1} for the 53 Mg ha^{-1} application of PG.

Increases in soluble Ca are due to the presence of the relatively large amounts of Ca present in the PG (29-34% CaO in PG, Dudas and Rutherford, 1992). With increased application of PG it would be expected that there be an accompanying increase in soluble Ca in the zone of PG application and possibly at greater depths. At Site 1, soluble Ca levels levelled off in the 0-10 cm zone of PG application at rates of application greater than 13 Mg ha^{-1}. There were no differences in soluble Ca levels among any of the PG application rates (excluding the 0 Mg ha^{-1} rate) in the 0-10 cm layer at Sites 2 and 3. This is most likely due to gypsum being a slightly soluble salt in aqueous solution, dissolving to approximately 15 mmol L^{-1} (Shainberg et al., 1989). This corresponds with the concentrations of soluble Ca measured in the soil solution of the 0-10 cm soil layer at each of the three sites. The amount of soluble Ca at the 53 Mg ha^{-1} rate of PG application in the 0-10 cm zone of application was 13.9, 15.6 and 18.6 mmol L^{-1} for Sites 1, 2 and 3, respectively. The dissolution of PG in aqueous Na solutions increases as the concentration of Na increases (Keren and Shainberg, 1981), thus accounting for a high dissolution rate in the soils with high levels of Na. Although the soil at Site 3 had low levels of soluble Na, granular structure and small aggregate sizes may have been a factor in that there is a larger surface area for exchange of Ca for other exchangeable ions. This may have had a limited effect on raising equilibrium Ca levels by releasing diverse ions into the soil solution (Shainberg et al., 1989).

Concentrations of soluble Mg at Site 1 increased significantly with the application of the lowest rate of PG in the 0-10 cm surface layer (Table 3.1). Soluble Mg increased from 0.7 mmol L^{-1} in the 0 Mg ha^{-1} rate to 1.7, 2.9, 2.9 and 2.8 mmol L^{-1} for the 6, 13, 26 and 53 Mg ha^{-1} application rates, respectively. The distribution of soluble Mg throughout the soil profile at Site 2 (Table 3.2) was similar to that of soluble Ca. Concentrations of soluble Mg in the 0-10 and 10-25 cm depth intervals increased

significantly with the application of PG. In the 0-10 cm layer, all rates of PG application increased soluble Mg significantly, with no significant differences among rates. In the 10-25 cm depth interval, all rates of PG application also increased levels of soluble Mg, but the 53 Mg ha^{-1} resulted in significantly higher levels than the lower treatment rates. Levels of soluble Mg at Site 3 increased significantly for all rates of PG application with no significant differences occurring among the 6, 13, 26 and 53 Mg ha^{-1} rates at the 0-10 and 10-25 cm depth intervals (Table 3.3). Increases in the concentration of soluble Mg from the 0 Mg ha^{-1} rate to the 53 Mg ha^{-1} rates were from 2.5 to 4.6 mmol L^{-1} and 0.8 to 4.0 mmol L^{-1} in the 0-10 and 10-25 cm depths, respectively. Soluble Mg in the 25-40 cm depth interval also increased significantly with the application of 13, 26 and 53 Mg ha^{-1} of PG with no significant differences among these rates.

Although PG contains relatively small amounts of Mg (<0.05%, May and Sweeney, 1983), some of the Mg accumulation, especially at the higher rates, may be due to solubilization of Mg in PG. Dissolution of Mg-containing calcite due to the acidic PG may also be another source of Mg. The displacement of Mg from soil exchange sites into the soil solution by the excess Ca present in the soil may also be a factor in the increased levels of soluble Mg in the 0-10 cm layer at Site 1, 2 and 3. Increases in soluble Mg at lower depth intervals at Sites 2 and 3 may be due to lower levels of sodicity, existence of soil structure and decreased clay content, thus allowing increased downward movement of water.

Concentrations of soluble Na in the profile at Site 1 remained relatively constant in the 0-10 cm layer (Table 3.1) with the application of PG, while increases in soluble Na with increased application of PG at the lower depth intervals were not significant. Increases in soluble Na with increased application rates of PG were observed throughout the minesoil profile at Site 2, with a significant increase occurring in the 10-25 cm depth interval for the 53 Mg ha^{-1} rate of application (Table 3.2). At Site 3 significant increases in the levels of soluble Na were measured in the 10-25 and 25-40 cm depth intervals

(Table 3.3). All rates of PG addition above the 0 Mg ha^{-1} rate at Site 3 significantly increased Na , with the 26 and 53 Mg ha^{-1} rates having significantly higher levels than the 6 and 13 Mg ha^{-1} rates at the 10-25 cm depth. Only the 26 and 53 Mg ha^{-1} rates of PG application resulted in significant increases in soluble Na for the 25-40 cm depth interval.

Levels of soluble Na were similar to those of Mg. Again, increased levels of soluble Na in the soil solution may have been due the dissolution of small amounts of Na in PG (0.03-0.05%, Dudas and Rutherford, 1992). Displacement of Na from exchange sites into the soil solution by elevated levels of soluble Ca may also have contributed to the increased levels of soluble Na, especially in the lower depth intervals of Sites 2 and 3. Significant downward movement of Ca, Mg, and Na at Sites 2 and 3, but not at Site 1, may be attributed to a lack of soil structure and the presence of large clods at Site 1, and the presence of granular structure and smaller aggregate diameters at Site 2 and 3. Previous work by Chaudhry and Warkentin (1967) on effects of aggregate size on the exchange of Na from soils by leaching with gypsum showed that exchange from larger aggregates resulted in slower exchange than from smaller aggregates due to the smaller surface area of the larger aggregates. This may have accounted for the lack of any significant downward movement of soluble Ca, Mg and Na at Site 1. Also the initially high levels of Na and high clay content at Site 1 likely resulted in a relatively low hydraulic conductivity reducing water infiltration and percolation, subsequently reducing the advancement of Ca into the soil profile.

3.1.3.ii Electrical conductivity, SAR and pH .

The application of PG, which increases the amount of dissolved salts in the soil solution, significantly increased the electrical conductivity (EC) over the 0 Mg ha^{-1} application rate, an indication of soil salinity, of the surface soil (0-10 cm) at all sites and at all rates of application (Table 3.1, 3.2 and 3.3). No significant differences were observed among the 6, 13, 26 and 53 Mg ha^{-1} rates at Sites 2 and 3, with only the 6 Mg ha^{-1} rate being significantly different from the 13, 26 and 53 Mg ha^{-1} rates at Site 1 in the

surface 0-10 cm. No significant increases in EC due to PG addition were observed with depth at Site 1. Significant increases in EC were measured in the soil solution of the 10-25 cm depth interval of Site 2, and the 10-25 and 25-40 cm depth intervals of Site 3. Increased salinity at lower depths is due to the downward movement of dissolved PG constituents (namely Ca, Mg and SO_4) and Ca, Mg and especially Na ions which have been displaced from soil exchange sites by the increased levels of soluble Ca and have been leached.

Large increases in soluble Ca, as a result of PG application, decreased SAR, an indicator of soil sodicity, significantly in the 0-10 cm surface layer at all three sites. No significant differences were observed between the 6, 13, 26 and 53 Mg ha^{-1} rates of addition nor were there any significant differences at greater depths. The lack of any significant changes in SAR at lower depth intervals may be due to the downward movement of displaced Na coupled with the downward movement of Ca from dissolved PG. The net effect being that the Na and Ca cancel each other out in relation to SAR.

Application of PG decreased soil pH significantly in the 0-10 cm surface layer at all three sites. At Site 1, a significant decrease in pH in the 0-10 cm layer from 7.5 in the 0 Mg ha^{-1} rate to 6.8 and 6.3 for the 26 and 53 Mg ha^{-1} rates, respectively, was measured (Figure 3.6a). Significant increases in acidity were measured at rates of 13, 26 and 53 Mg ha^{-1} at Site 2 (Figure 3.6b), and pH was decreased significantly, compared to the 0 Mg ha^{-1} rate, at all rates of PG application at Site 3 (Figure 3.6c). Decrease in pH with increased application of PG is due to impurities in the PG, namely sufuric and phosphoric acids.

3.1.4 Conclusions

Addition of phosphogypsum to all three sites resulted in significant decreases in the SAR at all rates of application in the 0-10 cm soil surface layer in a span of 16 months. Site 1, having the highest initial SAR values and the poorest soil structure of the three

sites, showed the least downward movement of dissolved PG constituents and the lowest level of Ca in the 0-10 cm layer, likely due to the lower surface area of aggregates exposed to PG. Downward movement of dissolved PG constituents at Sites 2 and 3 was increased, which can be attributed to lower initial sodium contents, presence of relatively stable soil structure, thus more surface area for exchange with Ca leading to a more complete dissolution of PG, and for Site 3, a higher sand content. Results obtained from Sites 2 and 3 have shown that PG, even at the low 6 Mg ha^{-1} rate of addition, increases the electrolyte concentration, as shown by EC, and has provided substantial amounts of Ca needed for exchange with Na. Reclamation of Site 3 may not be needed, from a salinity/sodicity standpoint, considering the low baseline Na and SAR values. Considering the low levels of salinity/sodicity at Site 2, and the results obtained one year after the application of PG, it can be concluded that low rates of PG (6 Mg ha^{-1}) would be needed for the reclamation of this site. Site 1, however, may require higher rates of PG application than Site 2 for reclamation; i.e. levels of exchangeable Na and SAR values must be lowered to below critical values. Due to the presence of large clods on the soil surface and massive structure directly beneath the plow layer, larger amounts of PG (13-26 Mg ha^{-1}) and a longer time span may be required to fully reclaim this site to depths greater than 10 cm.

Table 3.1. Chemical characteristics of PG-ammended soil at Site 1.

Application rate (Mg ha^{-1})	pH (water)	EC (dS m^{-1})	Soluble cations (mmol L^{-1}) Ca	Mg	Na	SAR
		0-10 cm depth interval				
0	7.5 a	1.1 c	1.6 c	0.7 c	9.1	6.0 a
6	7.2 ab	1.9 b	6.0 b	1.7 b	10	3.7 b
13	7.0 ab	2.9 a	12 a	2.9 a	10 ns	2.7 b
26	6.8 bc	2.8 a	14 a	2.9 a	9.0	2.2 b
53	6.3 c	3.0 a	14 a	2.8 a	11	2.7 b
		10-25 cm depth interval				
0	7.5	2.1	2.9 b	1.1	16	8.7
6	7.4	2.6	4.4 ab	1.4	19	8.4
13	7.3 ns	3.5 ns	8.1 ab	2.5 ns	24 ns	7.7 ns
26	7.2	3.4	9.9 a	2.9	20	5.7
53	6.6	3.0	7.4 ab	2.2	24	7.9
		25-40 cm depth interval				
0	6.6 c	3.7	6.7	2.2	28	10
6	6.8 bc	3.6	5.7	1.8	31	12
13	7.3 a	4.5 ns	8.1 ns	2.7 ns	38 ns	12 ns
26	6.8 abc	4.0	7.2	2.6	32	10
53	7.1 ab	4.6	9.0	2.7	37	11
		40-55 cm depth interval				
0	6.2 b	3.7	5.8	2.0	32	12
6	7.2 a	3.2	4.1	1.3	30	13
13	7.2 a	4.8 ns	8.2	2.7 ns	41 ns	13 ns
26	6.6 ab	5.1	7.9	2.7	42	13
53	7.0 ab	4.9	9.5	3.0	40	11

*individual treatment means within a column for a given depth followed by the same letter are not significantly different as determined by DMR ($P<0.05$), ns=not significant.

Table 3.2. Chemical characteristics of PG-amended soil at Site 2.

Application rate (Mg ha^{-1})	pH (water)	EC (dS m^{-1})	Soluble cations (mmol L^{-1}) Ca	Mg	Na	SAR
		0-10 cm depth interval				
0	6.0 a	1.8 b	4.4 b	2.2 b	7.1	2.8 a
6	5.7 ab	3.2 a	13 a	4.6 a	9.4	2.2 ab
13	5.6 b	3.2 a	15 a	4.5 a	8.9 ns	2.0 b
26	5.4 b	3.0 a	15 a	3.9 a	8.1	1.9 b
53	5.5 b	3.4 a	16 a	4.3 a	10	2.2 ab
		10-25 cm depth interval				
0	6.9	1.2 c	3.2 b	1.2 c	6.2 b	3.0
6	6.3	1.4 bc	3.6 b	1.7 b	6.4 b	2.7
13	6.5 ns	1.7 b	4.4 b	2.0 b	7.5 ab	3.0 ns
26	6.7	1.8 b	4.8 b	2.1 b	7.5 ab	2.9
53	6.6	2.8 a	9.0 a	3.6 a	10 a	2.9
		25-40 cm depth interval				
0	7.1	1.4	2.8	1.3	7.3	3.6
6	7.0	1.7	4.2	1.8	8.1	3.4
13	7.3 ns	1.6 ns	3.8 ns	1.6 ns	8.5 ns	3.7 ns
26	7.3	1.9	5.0	2.0	9.5	3.6
53	7.0	2.0	4.9	2.0	9.6	3.7
		40-55 cm depth interval				
0	7.1	1.5	3.6	1.7	8.0	3.7
6	7.0	1.7	4.3	1.9	8.6	3.5
13	7.3 ns	1.6 ns	3.6 ns	1.6 ns	8.5 ns	3.8 ns
26	7.3	2.0	5.2	2.2	9.9	3.6
53	7.1	2.1	5.4	2.3	10	3.6

*individual treatment means within a column for a given depth followed by the same letter are not significantly different as determined by DMR ($P<0.05$), ns=not significant.

Table 3.3. Chemical characteristics of PG-amended soil at Site 3.

Application rate (Mg ha^{-1})	pH (water)	EC (dS m^{-1})	Soluble cations (mmol L^{-1}) Ca	Mg	Na	SAR
		0-10 cm depth interval				
0	5.7 a	1.7 b	6.1 b	2.5 b	1.4	0.47 a
6	5.4 b	3.0 a	16 a	4.1 a	1.3	0.30 b
13	5.3 c	3.0 a	17 a	3.9 a	1.2 ns	0.26 b
26	5.4 bc	2.8 a	16 a	3.9 a	1.4	0.31 b
53	5.3 c	3.3 a	19 a	4.6 a	1.6	0.34 b
		10-25 cm depth interval				
0	5.9	0.6 b	1.6 b	0.8 b	1.3 c	0.82
6	5.8	1.6 a	6.4 a	2.6 a	1.8 b	0.64
13	5.9 ns	1.8 a	7.1 a	2.8 a	1.6 b	0.52 ns
26	5.6	2.1 a	8.8 a	3.6 a	2.2 a	0.66
53	5.4	2.3 a	9.9 a	4.0 a	2.1 a	0.56
		25-40 cm depth interval				
0	5.4	0.5 b	1.0	0.5 b	1.3 b	1.1
6	6.0	1.9 ab	2.6	1.3 ab	2.1 ab	1.1
13	5.8 ns	1.1 ab	3.6 ns	1.8 a	1.8 ab	0.8 ns
26	5.8	1.1 ab	3.3	1.7 a	2.5 a	1.2
53	5.4	1.5 a	5.1	2.4 a	2.5 a	1.0
		40-55 cm depth interval				
0	5.3	0.31	0.6	0.4	0.7	0.9
6	6.4	0.51	1.1	0.7	2.2	0.6
13	5.9 ns	0.69 ns	1.9 ns	1.0 ns	1.1 ns	0.7 ns
26	6.2	0.70	1.4	1.0	2.4	1.6
53	5.9	1.0	3.0	1.6	2.4	1.2

*individual treatment means within a column for a given depth followed by the same letter are not significantly different as determined by DMR ($P<0.05$). ns=not significant.

3.1.5 References

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3.2 Influence of phosphogypsum on soil surface strength.

3.2.1 Introduction

Formation of soil surface crusts is a feature common to dispersive soils, i.e. soils with unstable structure. The physical mechanism of crust formation can be summarized as follows (Awadhwal and Thierstein, 1985): due to the wetting and impact of raindrops soil aggregates slake and small particles, like silt and clay, become detached from larger grains (sand) and disperse at the soil surface. These small particles form a suspension in the water and move within the upper soil layer through the voids and between soil grains. Due to the capillary suction of the lower layers, voids become clogged with fine particles and a thin layer is formed at the soil surface. Densification of the soil surface layer during wetting and subsequent drying is enhanced due to: tendency of platy particles (clay), in a state of semi-suspension, to settle with their long axis in a horizontal direction; attraction among adjoining particles; and retreat of water held in place between particles during drying (Awadhwal and Thierstein, 1985). McIntyre (1958) described soil crusts as having two distinct components; a thin, compact, skin seal (0.1 mm) over the soil surface formed by raindrop impact and a washed-in region of decreased porosity due mainly to washing in of fine particles. Permeability was 200 and 2000 times lower in the washed-in zone and skin seal, respectively, than the underlying soil (McIntyre, 1958).

Formation of surface crusts can greatly reduce water infiltration, due to low permeability, and restrict seedling emergence. The limiting value of crust strength inhibiting emergence depends upon soil moisture; at a given crust strength, seedling emergence is lowest where the moisture is lowest (Awadhwal and Thierstein, 1985). Various measurements of soil crust strength have been made in relation to seedling emergence. Using the modulus of rupture as an index of soil strength, the emergence of bean seedlings decreased from 100 to 0% as the crust strength increased from 10.8 to 27.3 kPa (Richards, 1953). The limiting modulus of rupture for corn emergence is between 120 and 250 kPa (Allison and Moore, 1956). Emergence of wheat, sorghum and soybean

seedlings are also limited with increased crust strengths. Less than 40% emergence occurred when modulus of rupture was greater than 50 kPa when soil was at 1/4 available moisture (Hanks and Thorpe, 1957).

Electrolyte concentrations of applied water, rain or irrigation, and the exchangeable sodium content of the soil play a major role in determining crust formation and strength. Aggregate disintegration and clay dispersion due to chemical properties predominate in the formation of the wash-in region of soil crusts (Shainberg, 1985). Soil surfaces are particularly susceptible to the chemistry of the applied water, because of the mechanical action of the falling raindrops and the chemical freedom for particle movement at the soil surface (Oster and Schroer, 1979).

Kazman et al. (1983) observed that infiltration rates of soils with an ESP as low as 2 drastically decreased after addition of distilled water (i.e. low electrolyte concentrations). With additions of PG, infiltration rates were maintained at higher levels due to the release of electrolytes in the surface soil solution. Increases in exchangeable sodium content of soils can also influence crust strengths. Modulus of rupture increases linearly with increasing exchangeable sodium (Reeve et al., 1954). The application of 2% gypsum (by weight of soil) decreased the modulus of rupture (determined at the plastic limit) from >20 kPa to <15 kPa (Shanmuganathan and Oades, 1983). Graveland and Toogood (1963) observed that with the application of 18 Mg ha^{-1} gypsum to soil with an initial ESP of 16.1, the modulus of rupture decreased from 260.5 to 45 kPa, and the ESP was reduced to 6.5. Phosphogypsum can provide high electrolyte levels in the soil solution and at the same time replace Na on exchange sites for Ca, decreasing the dispersivity of the surface soil and thus decreasing crusting potential.

The objectives of this study were to determine the effects of PG, applied at various rates, on soil surface structure *in situ* and in the laboratory.

3.2.2 Materials and Methods

Please refer to Section 2.3.

3.2.3 Results and Discussion

At all sites the application of PG at all rates of application above 0 Mg ha^{-1} and on all dates of measurement, with the exception of 6 Mg ha^{-1} on August 19, 1991 and 53 Mg ha^{-1} on September 10, resulted in significant decreases of *in situ* surface strength (ISS), and hence surface crust strength (Figure 3.7a, b and c). Results obtained in this study agree with those of previous research (Loveday and Scotter, 1966; Shanmuganathan and Oades, 1983; Rolston et al., 1991) where gypsum resulted in reduced soil crust strength. Soil moisture of the soil crust increased as the PG application rate increased compared to the 0 Mg ha^{-1} rate on four of the seven measurement dates (Figure 3.8) but only for certain rates of application. A long dry spell during the month of September (only 8 mm of rainfall from September 1 to 25) may have been a factor in the non-significant difference among moisture measurements at all three sites for the September 25 measurement date.

The modulus of rupture (MOR) of the surface soil samples from Site 1 decreased significantly with the application of PG (Figure 3.9). MOR decreased from 254 kPa in the 0 Mg ha^{-1} treatment to 230, 109, 60, and 41 kPa in the 6, 13, 26 and 53 Mg ha^{-1} rates of PG application, respectively, of which the 13, 26 and 53 Mg ha^{-1} rates were significantly different from the 0 Mg ha^{-1} rate. MOR of the Site 2 surface soil decreased significantly from 95 kPa in the 0 Mg ha^{-1} rate to 54 kPa for the 53 Mg ha^{-1} treatment. MOR of the Site 3 samples reacted a little differently than those from Sites 1 and 2. No significant differences were observed between the 0 Mg ha^{-1} rate and any of the PG treatments, however, the MOR of the 6 Mg ha^{-1} treatment (77 kPa) was significantly higher than that of the 53 Mg ha^{-1} treatment (53 kPa).

The MOR and the average ISS values were plotted for each of the three sites (Figure 3.9 a, b and c). Relatively comparable results were obtained from both methods of determining the crusting potential of the soil. A simple correlation between MOR and ISS, resulted in an r^2 value of 0.65 (Figure 3.10a). A significant correlation for 15 data

points needs an r^2 of 0.26 or higher. Correlations between ISS, SAR and electrical conductivity (EC), an indicator of solution electrolyte concentration, (Figure 3.10b) also resulted in fairly high correlation coefficients of 0.72 and 0.63 for the ISS vs SAR and ISS vs EC, respectively. Correlations between MOR, SAR and EC (Figure 3.10c) resulted in somewhat lower correlation coefficents than with ISS correlations, with r^2 values of 0.60 and 0.56 for the MOR vs SAR and MOR vs EC, respectively. Although correlations are significant, more data are required in order to obtain a better distribution of results accross the salinity spectrum than obtained in this study. Both the ISS and MOR results agree with previous research in that an increase in EC with a corresponding decrease in Na content will decrease the crusting potential of a soil (Agassi et al., 1981; Kazman et al., 1983). Conversely, an increase in Na with a decrease in EC will result in increased soil crusting potential, thus confirming the importance of maintaining a high electrolyte content of the soil water even with low levels of Na present.

3.2.4 Conclusions

The most dramatic responses to PG occurred in soils which had initially high SAR values (Site 1). As SAR decreased with increasing rates of PG application (Figure 3.5a), MOR and ISS of the soil also decreased significantly. The relationships between MOR and ISS to the level of sodium in the soil surface are positive linear, where an increase in Na in turn results in an increase in crust strength. MOR, a laboratory measurement of soil crusting potential, and ISS, an *in situ* method of determining surface soil strengths, may be comparable techniques. The results agree with previous research in that even at low levels of sodium in the soil, relatively high levels of electrolyte must be present in the infiltrating solution to reduce soil surface strength (Figure 3.10a and b). Levels of electrolyte concentration must, however, not limit plant growth. Considering modulus of rupture in relation to seedling emergence of previous research, it could be suggested that for cereal and small seeded crops a limiting crust strength for emergence could be set at 100 kPa.

therefore, where exchangeable sodium values are fairly high, such as in Site 1, application rates of 26 Mg ha^{-1} or higher may be required to decrease crust strength values to below 100 kPa. Rates less than 6 Mg ha^{-1} may maintain a crust strength less than 100 kPa at Site 2 due to the lower levels of exchangeable Na. Site 3 had very low initial levels of exchangeable Na and MOR and ISS values obtained in the Control treatment are already below 100 kPa. The application of PG at Site 3 was not needed to reduce surface crusting potential.

3.2.5 References

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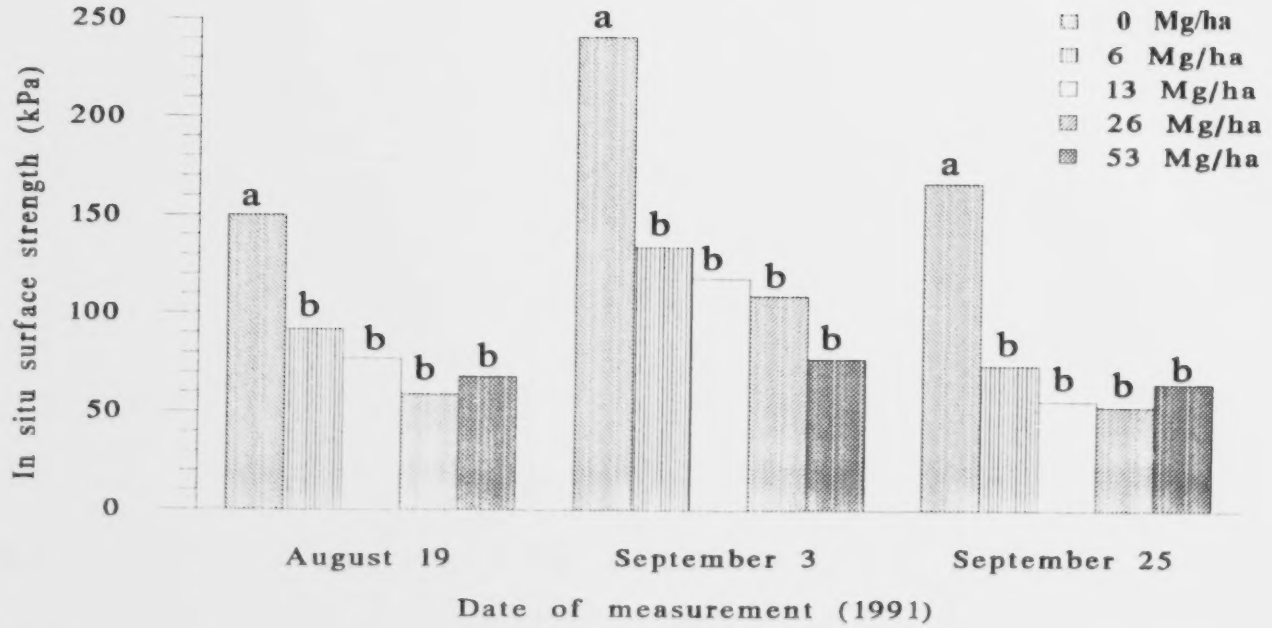

Figure 3.7a. In situ surface strength of PG-amended soil at Site 1. Letters within each date indicate significant differences by Duncan's Multiple Range Test at the 5% level.

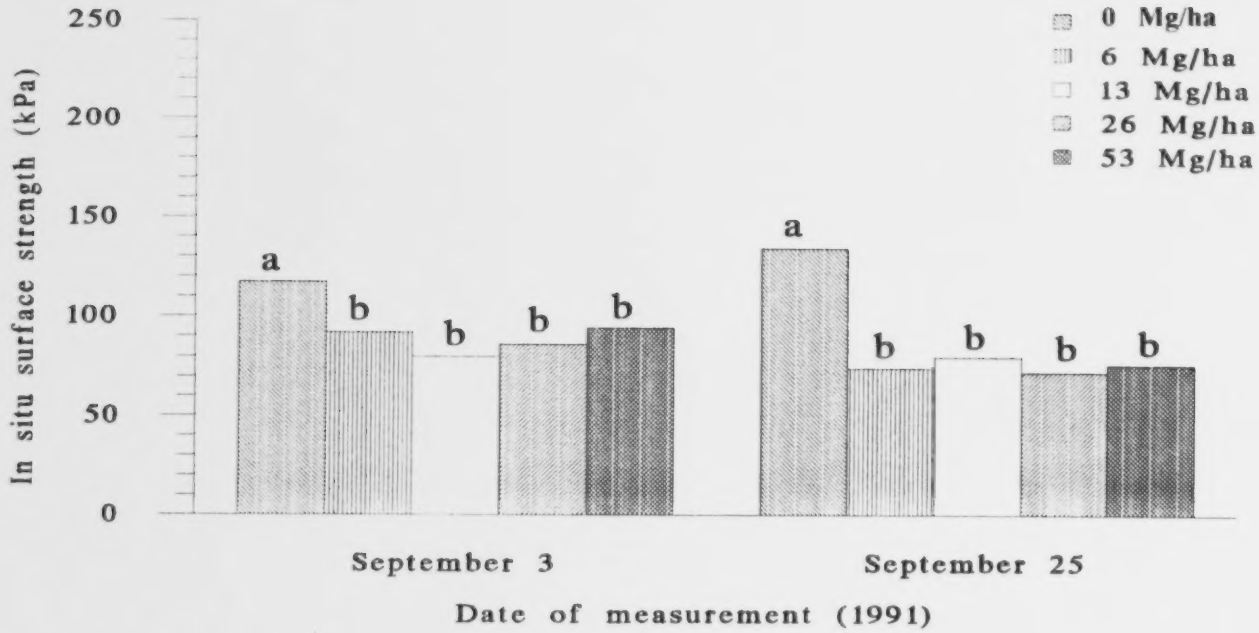

Figure 3.7b. In situ surface strength of PG-amended soil at Site 2. Letters within each date indicate significant differences by Duncan's Multiple Range Test at the 5% level.

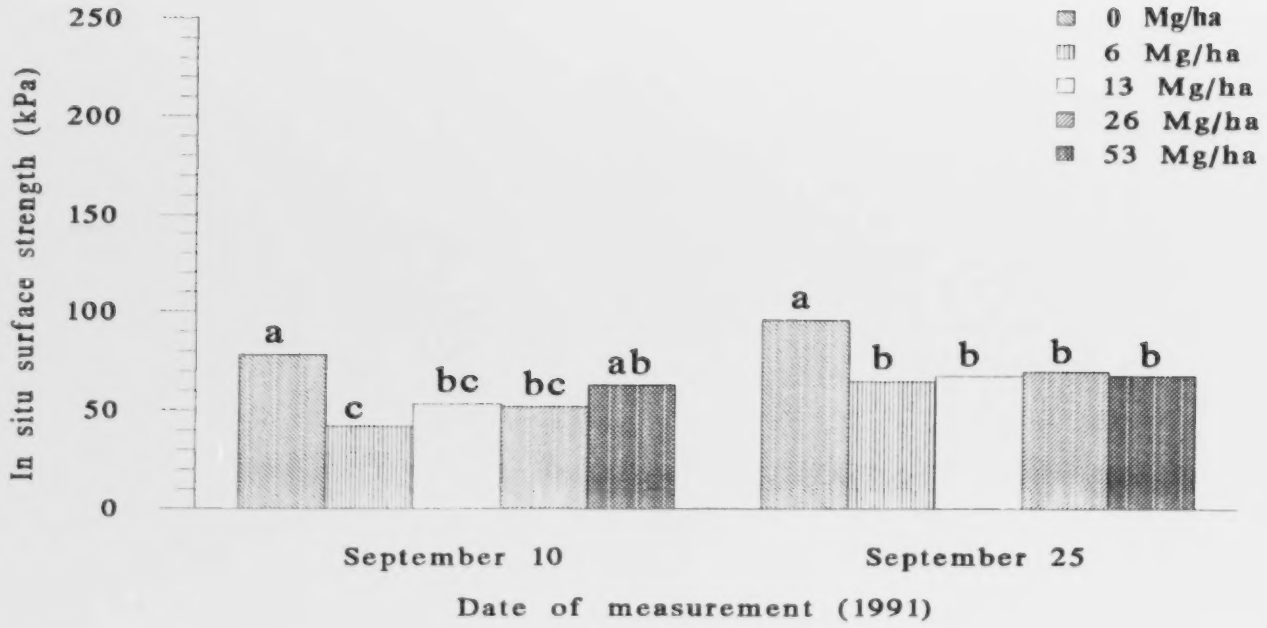

Figure 3.7c. In situ surface strength of PG-amended soil at Site 3. Letters within each date indicate significant differences by Duncan's Multiple Range Test at the 5% level.

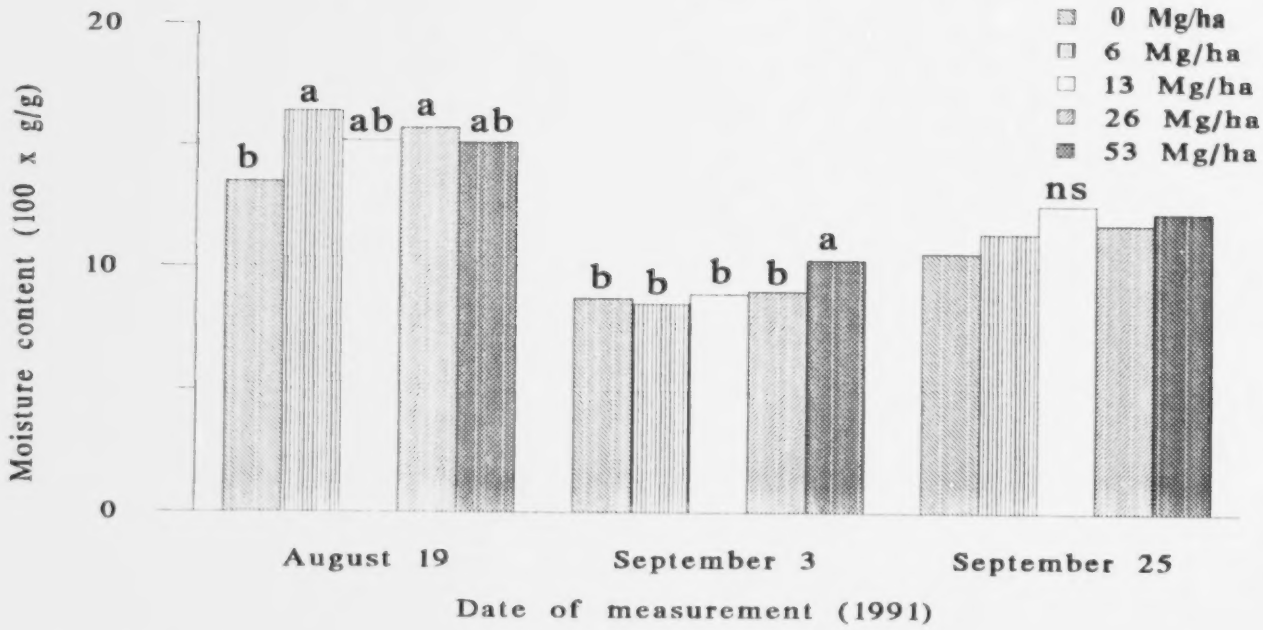

Figure 3.8a. Surface soil moisture of PG-amended soil at the time of surface strength measurements at Site 1. Letters within each date indicate significant differences by Duncan's Multiple Range Test at the 5% level, ns=not significant.

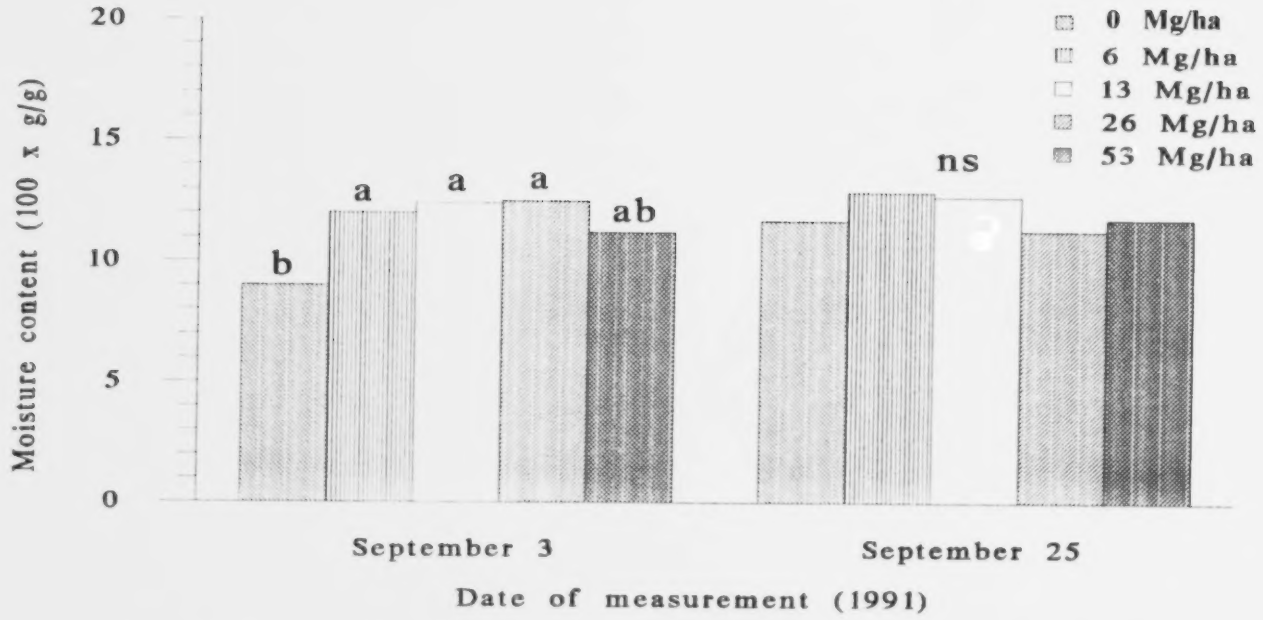

Figure 3.8b. Surface soil moisture content of PG-amended soil at the time of surface strength measurements at Site 2. Letters within each date indicate significant differences by Duncan's Multiple Range Test at the 5% level, ns=not significant.

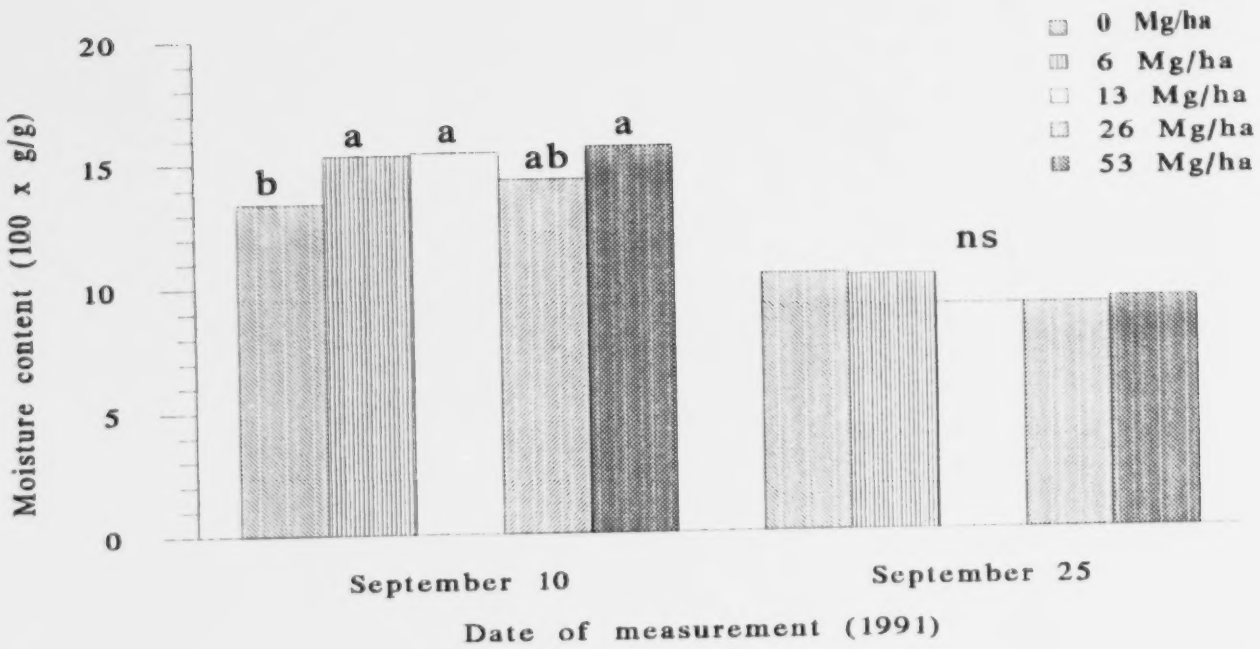

Figure 3.8c. Surface soil moisture content of PG-amended soil at the time of surface strength measurements at Site 3. Letters within each date indicate significant differences by Duncan's Multiple Range Test at the 5% level, ns=not significant.

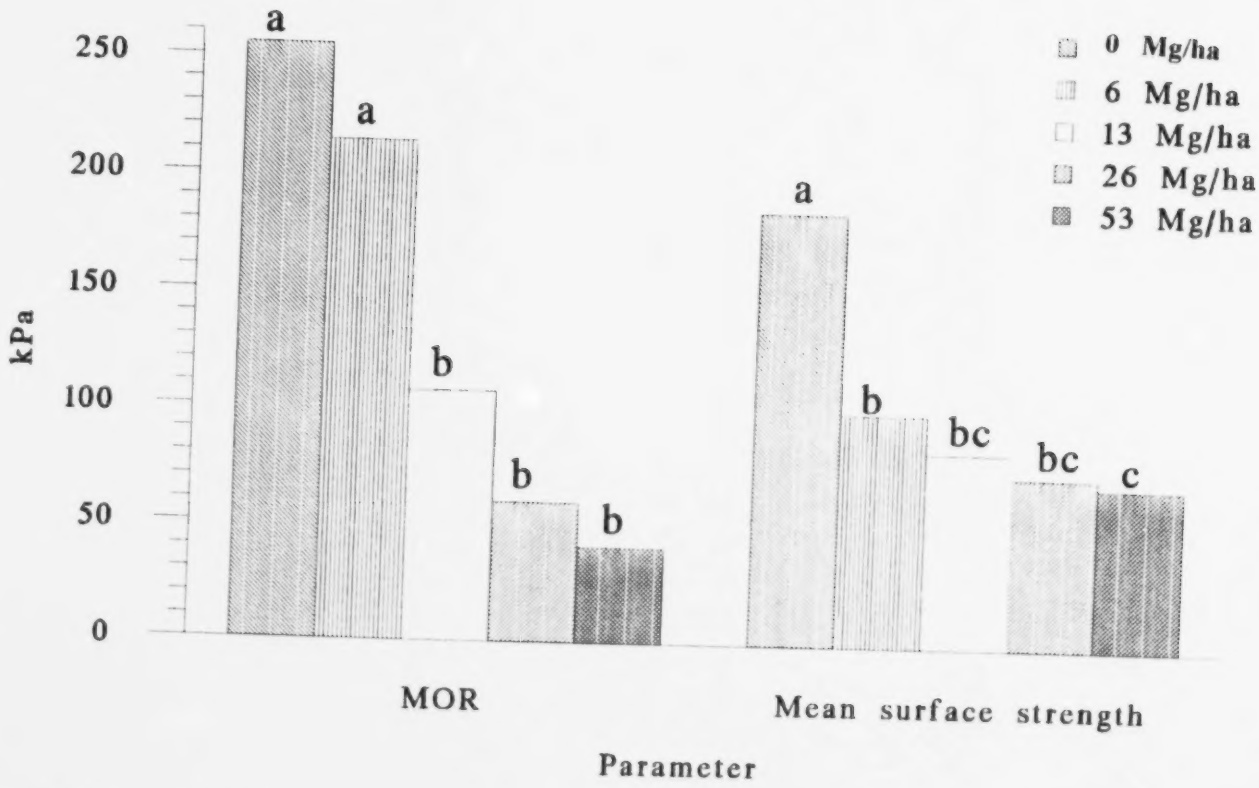

Figure 3.9a. Modulus of rupture (MOR) and date-averaged in situ surface strength of PG-amended soil at Site 1. Letters indicate significant differences by Duncan's Multiple Range Test at the 5% level.

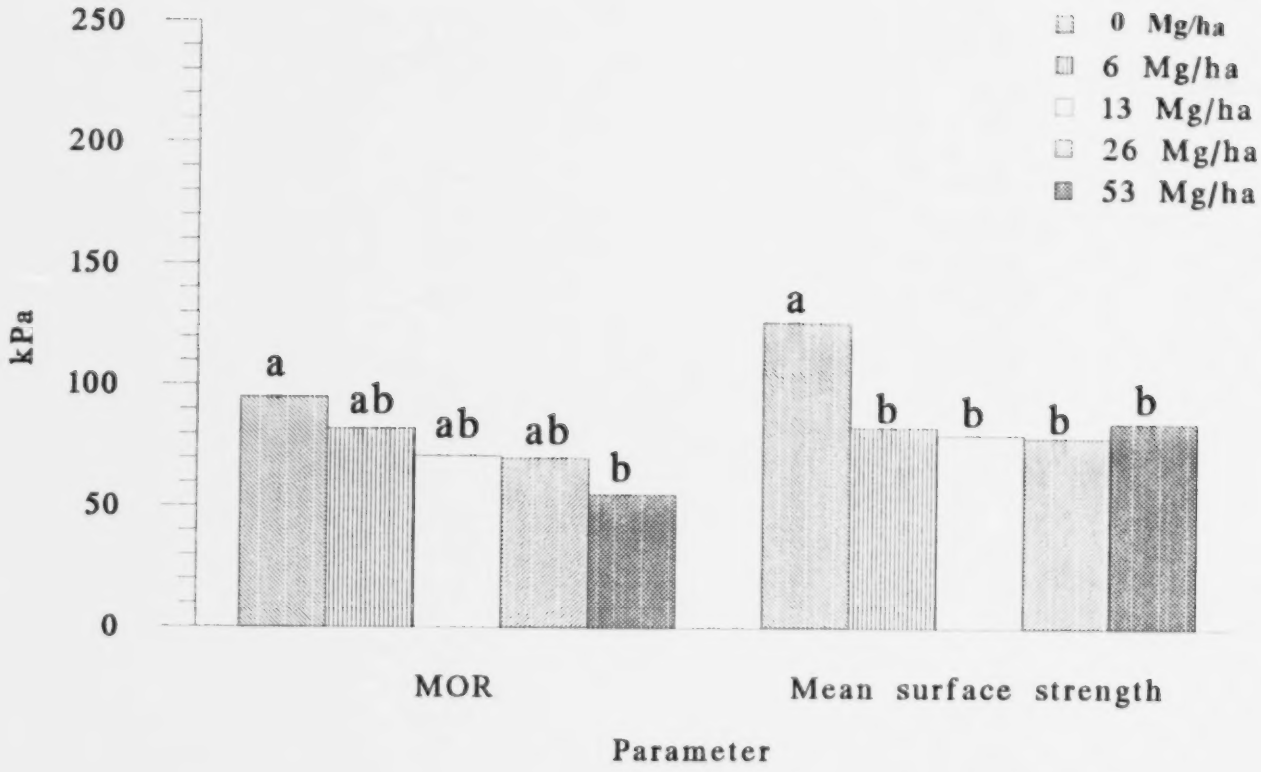

Figure 3.9b. Modulus of rupture (MOR) and date-averaged in situ surface strength of PG-amended soil at Site 2. Letters indicate significant differences by Duncan's Multiple Range Test at the 5% level.

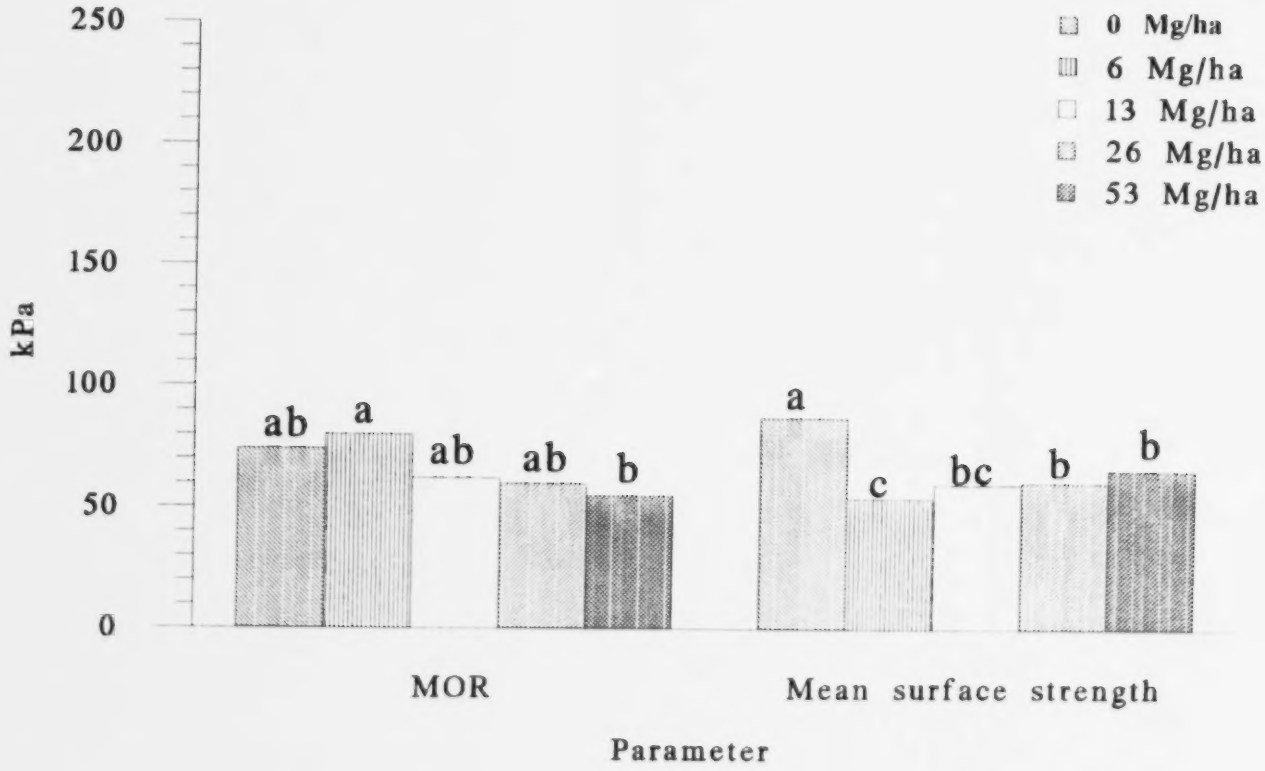

Figure 3.9c. Modulus of rupture (MOR) and date-averaged in situ surface strength of PG-amended soil at Site 3. Letters indicate significant differences by Duncan's Multiple Range Test at the 5% level.

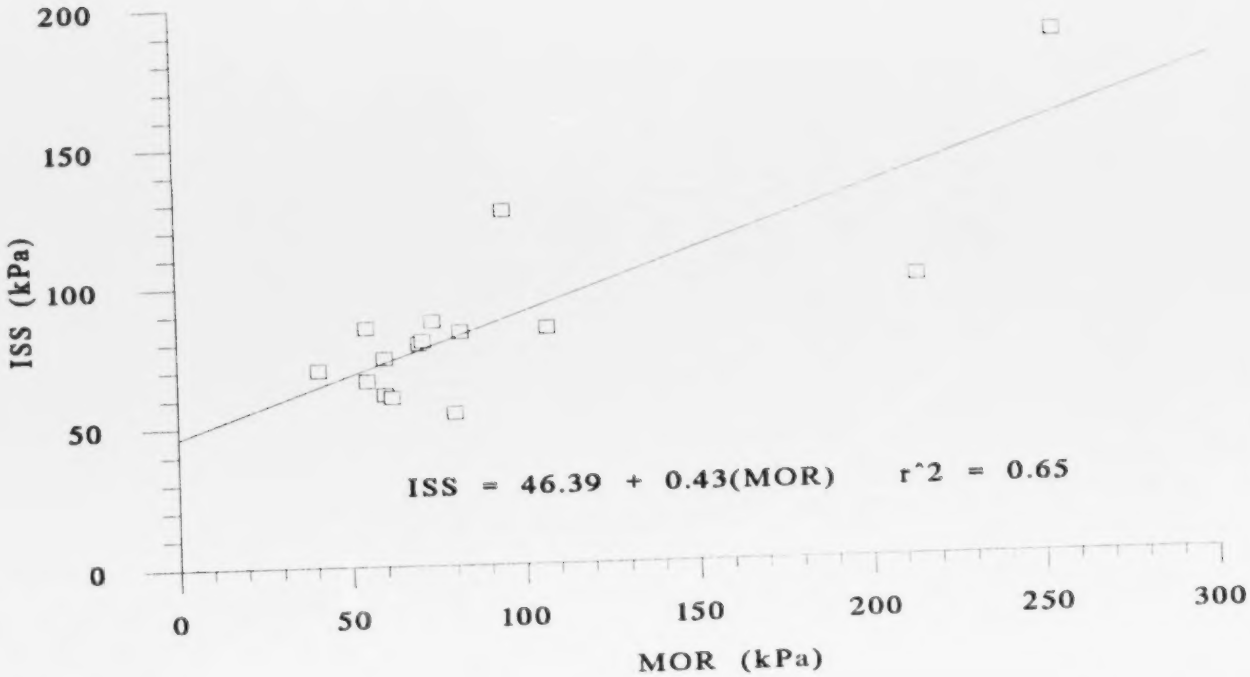

Figure 3.10a. Relationship between MOR and ISS measurements in PG-amended soils.

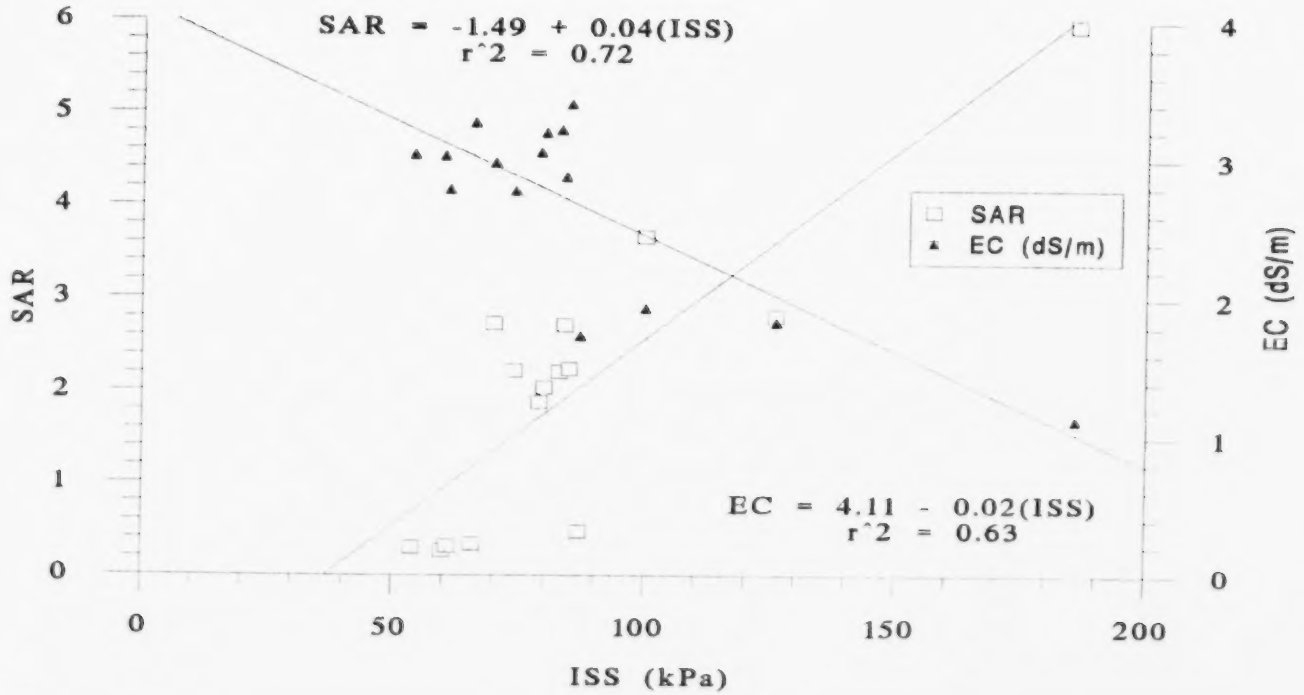

Figure 3.10b. Relationships between ISS, SAR and EC of PG-amended soils.

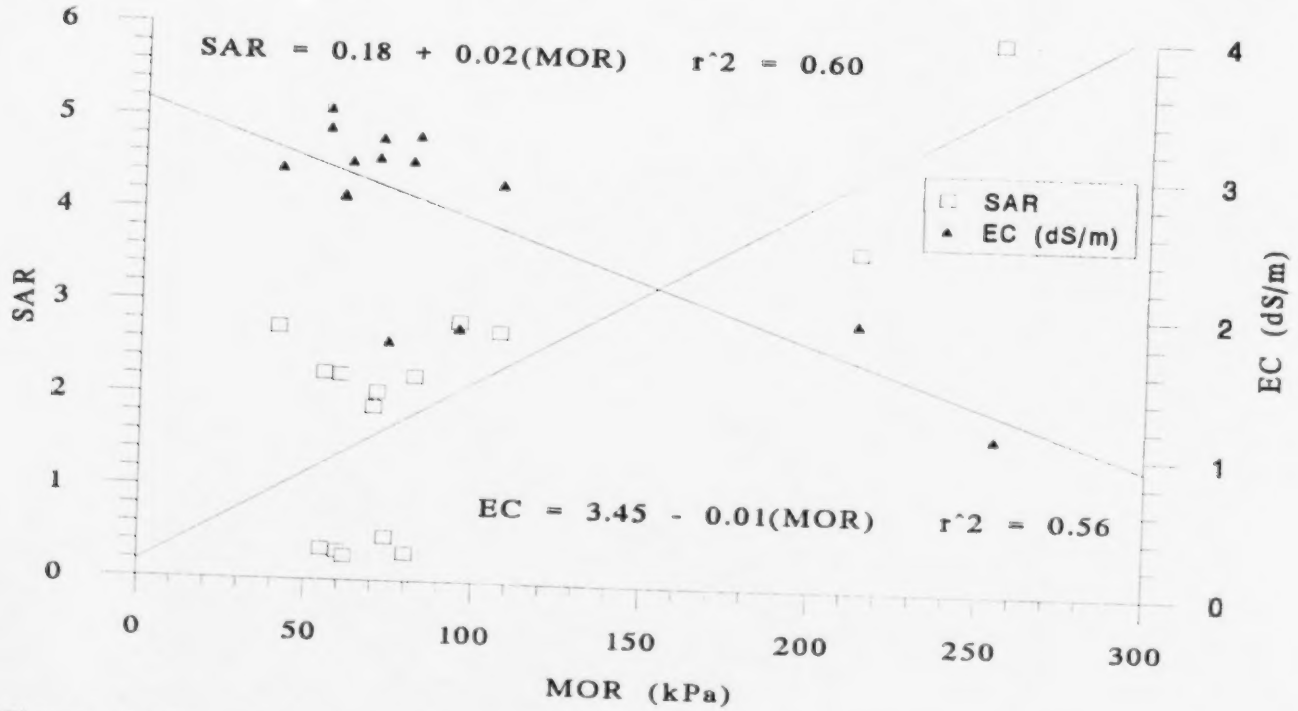

Figure 3.10c. Relationships between MOR, SAR and EC of PG-amended soils.

3.3 Size distribution and stability of aggregates in phosphogypsum-amended soil.

3.3.1 Introduction

In order to study the size distribution and stability of aggregates, the term 'aggregate' must first be defined. Kemper and Chepil (1965) defined an aggregate as a group of two or more primary particles (sand, silt or clay) which cohere to each other more strongly than to surrounding particles. Hillel (1982) defined soil tilth as: In soils with an appreciable amount of clay, the primary particles tend, under favorable circumstances, to group themselves into structural units known as secondary particles, or aggregates.

The size distribution and stability of soil aggregates is a decisive factor in the assessment of soil tilth. Hillel (1982) defined soil tilth as that physical condition in which the soil is in an optimally loose, friable, and porous assemblage of aggregates permitting free movement of water and air, easy cultivation and planting, and unobstructed germination and root growth. The size distribution of aggregates needed for optimal tilth would require a combination of aggregate sizes which allow relatively quick downward water movement but at the same time retain water for later plant use. Aggregates must also be stable in order to withstand the impact of raindrops or the disruptive forces of cultivation. The instability of aggregates can lead to the formation of dense surface crusts, creating a barrier for the infiltration of water and obstructing seedling emergence.

A prerequisite for aggregation is that the clay be flocculated (Hillel, 1982). As previously discussed in Section 3.1.1, the electrolyte concentration of percolating water (irrigation or rain water) and the presence of sodium in the soil solution are major factors in the dispersivity (non-flocculation) of soil aggregates. In order to initiate aggregate formation and increase stability, the detrimental effects of sodium must be overcome by first increasing the electrolyte concentration of the percolating solution and secondly,

replacing sodium with a cation, such as calcium, which enhances the flocculation of clay particles.

Use of calcium-containing products, such as lime, gypsum and gypsum by-products have been used extensively in trying to improve the structural stability of soils, especially at the soil surface. Stability of aggregates at the soil surface can have direct effects on infiltration rates. Application of phosphogypsum (PG) on the soil surface increased the final infiltration rate of a sandy soil with an ESP of 11.6 from 2 mm h^{-1} to 10 mm h^{-1} (Kazman et al., 1983). The dissolution of PG increases the electrolyte concentration of the soil solution and at the same time replaces Na on exchange sites with Ca (Shainberg et al., 1989), thus decreasing the dispersivity of the surface soil, in turn initiating the formation of aggregates.

The objectives of this study were to (1) determine the effects of PG, applied at various rates, on the size distribution and stability of surface aggregates and (2) to determine which rate(s) of PG would provide the most beneficial and/or detrimental results in terms of aggregate stability.

3.3.2 Materials and Methods

Please refer to Section 2.3.

3.3.3 Results and Discussion

Dry aggregate size distribution

The application of PG at Site 1 influenced the size distribution of dry aggregates significantly (Table 3.4). The percentage of aggregates, on a mass basis, greater than 6.3 mm was reduced from 50.1% in the 0 Mg ha^{-1} rate to 39.4, 30.4, 19.2, and 18.3% in the 6, 13, 26 and 53 Mg ha^{-1} treatments, respectively. A reduction in large aggregates results in a seedbed which contains smaller aggregates allowing for better seed to soil contact for the transfer of water and nutrients to the seed. The reduction in large aggregates (> 6.3

mm) coincided with a sharp increase in aggregates in the 1-4 mm size range. This percentage increased from 25.6% in the 0 Mg ha^{-1} rate to 32.4, 39.5, 44.0 and 43.9% in the 6, 13, 26 and 53 Mg ha^{-1} treatments, respectively. In soils containing a majority of aggregates in the 1-4 mm size ranges, weaker crusts develop and seedling emergence is increased (Braunack and Dexter, 1988). The MWD of soil aggregates can be used, as a single parameter, to represent the aggregate sizes of a soil sample. At Site 1, the MWD was significantly reduced from 6.52 mm in the 0 Mg ha^{-1} rate to 3.89 and 3.95 in the 26 and 53 Mg ha^{-1} treatments (Figure 3.13a).

Size distribution of aggregates at Site 2 also responded to the application of PG, but not to the same extent as at Site 1 (Table 3.5). Aggregates greater than 6.3 mm in size were reduced from 34.1% of the sample mass in the 0 Mg ha^{-1} rate to a low of 15.1% in the 13 Mg ha^{-1} treatment with a subsequent increase of aggregates in the 1-4 mm range from 30.7 to 41.7% in the 0 Mg ha^{-1} and 13 Mg ha^{-1} treatments, respectively. MWDs were also reduced significantly, from 5.67 mm in the 0 Mg ha^{-1} rate to 3.64, 3.34, 3.64 and 3.42 mm in the 6, 13, 26 and 53 Mg ha^{-1} treatments, respectively (Figure 3.13a).

Significant changes in the size distribution of aggregates as a result of PG addition were observed for the samples from Site 3 (Table 3.6), but the changes were not as dramatic as the results obtained from Site 1 and 2. Increased rates of PG at Site 3 increased the percentage of aggregates in the smaller size ranges (< 2 mm) and decreased the proportion of aggregates in the larger size ranges (> 6.3 mm). MWDs at Site 3 were decreased significantly with the addition of PG, from 3.6 mm in the Control to 2.7, 2.5 and 2.2 mm in the 13, 26 and 53 Mg ha^{-1} treatments, respectively (Figure 3.13a)

Aggregate stability

Significant changes in size distribution of wet-sieved aggregates as a result of PG addition were observed only in samples from Site 1 (Table 3.7 and Figure 3.12a). Increased rates of PG decreased the percentage of aggregates < 1 mm from 37% in the 0

Mg ha^{-1} rate to 22% in the 53 Mg ha^{-1} treatment and in turn increased the number of aggregates > 2 mm. Significant changes, due to PG addition, in the MWD of wet-sieved aggregates were only observed at Site 1. A significant increase in the wet MWD from 2.10 mm in the 0 Mg ha^{-1} rate to 2.84 mm in the 53 Mg ha^{-1} treatment was observed (Figure 3.13b).

In an effort to determine the difference in aggregate size from dry-seived to wet-seived conditions, the ratio of wet-seived MWD:dry-seived MWD was calculated: the MWD of water-seived aggregates was divided by the MWD of dry-seived aggregates for each treatment, thus giving the ratio of wet MWD:dry MWD. The higher the value obtained from this ratio, the more stable, or less erodible, the aggregates are.

Significant results due to PG addition were obtained from all sites for the wet MWD:dry MWD ratios (Figure 3.13c). At Site 1 wet MWD:dry MWD increased dramatically from 0.325 in the 0 Mg ha^{-1} treatment to 0.506 and 0.726 in the 26 and 53 Mg ha^{-1} application rates. At Site 2 the 6 Mg/ha^{-1} PG application rate significantly increased the wet MWD:dry MWD ratio to 0.474 from 0.256 at 0 Mg ha^{-1}. At Site 3 the wet MWD:dry MWD ratio was increased significantly from 0.601 in at 0 Mg ha^{-1} to 0.904 in the 53 Mg ha^{-1} PG application rate.

Decreased aggregate stability also corresponds to an increase in surface strength of the soil. Silt and clay particles from dispersed aggregates settle out on the soil surface to form a surface crust. Mean modulus of rupture (MOR) and *in situ* surface strength (ISS) from all sites were plotted against their corresponding wet MWD:dry MWD ratios (Figures 3.14 and 3.15). An r^2 of 0.276 and 0.390 was obtained from the MOR and ISS plots, respectively. Both figures show that less stable aggregates (those with lower wet MWD:dry MWD ratios) result in higher soil surface stengths. The relationship between aggregate stability and levels of sodium and calcium in the soil solution is also very important. Higher sodium adsorption ratios (SAR) result in an increased loss in aggregate size (Figure 3.16) due to increased dispersion with higher levels of sodium.

3.3.4 Conclusions

Application of PG resulted in significant changes in the size distribution of dry-aggregates. PG, in all cases, lowered the MWD of dry aggregates, thus improving seedbed quality. Aggregate stability was also increased with the application of PG, as measured by a ratio of wet MWD:dry MWD.

If a critical surface strength limit is set at 100 kPa (as described in section 3.2.4) and using Figures 3.14 and 3.15, acceptable wet MWD:dry MWD ratios should be > approximately 0.5, meaning that upon wet-seiving, wet MWD should not be reduced to more than one-half of its dry MWD. If wet MWD is less than one-half of its dry MWD, the potential for a soil crust strong enough to inhibit seedling emergence is likely increased. The SAR of surface soil must be below approximately 2.3 in order to prevent aggregates from eroding to below 50 % of their dry size (Figure 3.16).

At sites with high levels of sodium in the soil solution, such as Site 1, more than 26 Mg ha^{-1} of PG would be needed to maintain deterioration in aggregate size above the 50 % tolerance limit. At Site 2 none of the application rates of PG increase the wet MWD:dry MWD ratio above the 50 % mark. It may be possible that rates higher than 53 Mg ha^{-1} are needed. Something other than PG may be needed to help in maintaining aggregate stability. Amendments which would improve the organic matter content of the soil, such as manure or compost could be used. The application of PG at Site 3 was not needed for increasing aggregate stability since the Control treatment has a dry MWD:wet MWD ratio of above 0.5.

3.3.5 References

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Table 3.4 Aggregate size distribution (w/w) of dry-seived aggregates following application of phosphogypsum (August 7, 1991) at Site 1.

Size range (mm)	PG application rate				
	0 Mg ha^{-1}	6 Mg ha^{-1}	13 Mg ha^{-1}	26 Mg ha^{-1}	53 Mg ha^{-1}
< 0.125	0.009 b*	0.010 b	0.007 b	0.012 ab	0.017 a
0.125-0.25	0.011 b	0.013 b	0.014 b	0.020 a	0.023 a
0.25-0.5	0.029 b	0.035 b	0.040 b	0.057 a	0.057 a
0.5-1.0	0.070 c	0.089 bc	0.115 ab	0.152 a	0.151 a
1.0-2.0	0.111 c	0.147 bc	0.206 ab	0.237 a	0.233 a
2.0-4.0	0.145 b	0.177 ab	0.189 ab	0.203 a	0.206 a
4.0-6.3	0.124 a	0.135 a	0.125 a	0.130 a	0.130 a
6.3-9.5	0.118 a	0.127 a	0.103 ab	0.090 b	0.079 b
9.5-12.5	0.094 a	0.099 a	0.076 ab	0.051 b	0.046 b
12.5-25	0.173 a	0.149 ab	0.098 bc	0.046 c	0.056c
> 25	0.116 a	0.019 a	0.027 a	0.005 a	0.002 a

*Means in a row followed by a common letter are not significantly different (P=0.05) using DMR test.

Table 3.5 Aggregate size distribution (w/w) of dry-seived aggregates following application of phosphogypsum (August 7, 1991) at Site 2.

Size range (mm)	PG application rate				
	0 Mg ha^{-1}	6 Mg ha^{-1}	13 Mg ha^{-1}	26 Mg ha^{-1}	53 Mg ha^{-1}
< 0.125	0.014 a*	0.019 a	0.015 a	0.022 a	0.011 a
0.125-0.25	0.029 c	0.039 ab	0.033 abc	0.043 a	0.030 bc
0.25-0.5	0.069 b	0.097 a	0.095 a	0.098 a	0.090 a
0.5-1.0	0.129 b	0.183 a	0.193 a	0.188 a	0.191 a
1.0-2.0	0.157 d	0.206 bc	0.242 a	0.202 c	0.236 ab
2.0-4.0	0.150 b	0.169 ab	0.175 a	0.160 ab	0.176 a
4.0-6.3	0.110 a	0.104 ab	0.096 b	0.099 ab	0.098 b
6.3-9.5	0.094 a	0.082 ab	0.066 c	0.074 bc	0.072 bc
9.5-12.5	0.070 a	0.043 b	0.040 b	0.039 b	0.054 b
12.5-25	0.148 a	0.053 b	0.043 b	0.062 b	0.037 b
> 25	0.029a	0.005 b	0.002 b	0.015 ab	0.005 b

*Means in a row followed by a common letter are not significantly different (P=0.05) using DMR test.

Table 3.6 Aggregate size distribution after dry-seiving aggregates following application of phosphogypsum (September 3, 1991) at Site 3.

Size range (mm)	PG application rate				
	0 Mg ha^{-1}	6 Mg ha^{-1}	13 Mg ha^{-1}	26 Mg ha^{-1}	53 Mg ha^{-1}
< 0.125	0.050 d*	0.053 cd	0.065 bc	0.072 ab	0.084 a
0.125-0.25	0.050 c	0.057 bc	0.064 b	0.068 ab	0.078 a
0.25-0.5	0.111 c	0.115 bc	0.135 ab	0.142 a	0.145 a
0.5-1.0	0.159 b	0.163 b	0.189 a	0.191 a	0.189 a
1.0-2.0	0.170 b	0.185 a	0.187 a	0.188 a	0.190 a
2.0-4.0	0.150 a	0.162 a	0.147 a	0.149 a	0.149 a
4.0-6.3	0.088 ab	0.105 a	0.078 b	0.078 b	0.078 b
6.3-9.5	0.077 a	0.071 a	0.054 b	0.049 b	0.050 b
9.5-12.5	0.053 a	0.050 a	0.038 b	0.026 c	0.024 c
12.5-25	0.059 a	0.037 b	0.030 bc	0.028 bc	0.012 c
> 25	0.033 a	0.003 b	0.014 ab	0.009 b	0.000 b

*Means in a row followed by a common letter are not significantly different (P=0.05) using DMR test.

Table 3.7 Aggregate size distribution after wet-sieving phosphogypsum-amended soil at Site 1.

Size range (mm)	PG application rate				
	0 Mg ha^{-1}	6 Mg ha^{-1}	13 Mg ha^{-1}	26 Mg ha^{-1}	53 Mg ha^{-1}
9.5-4.0	0.11 b*	0.08 ab	0.12 b	0.09 b	0.06 a
4.0-2.0	0.08 a	0.06 a	0.09 a	0.08 a	0.05 a
2.0-1.0	0.12 a	0.11 a	0.14 a	0.13 a	0.09 a
1.0-0.5	0.20 a	0.19 a	0.22 a	0.25 a	0.18 a
0.5-0.25	0.18 ab	0.17 ab	0.17 a	0.20 a	0.17 b
0.25-0.125	0.16 a	0.16 ab	0.14 a	0.14 a	0.16 b
< 0.125	0.14 ab	0.21 bc	0.13 a	0.12 abc	0.29 c

*Means in a row followed by a common letter are not significantly different (P=0.05) using DMR test.

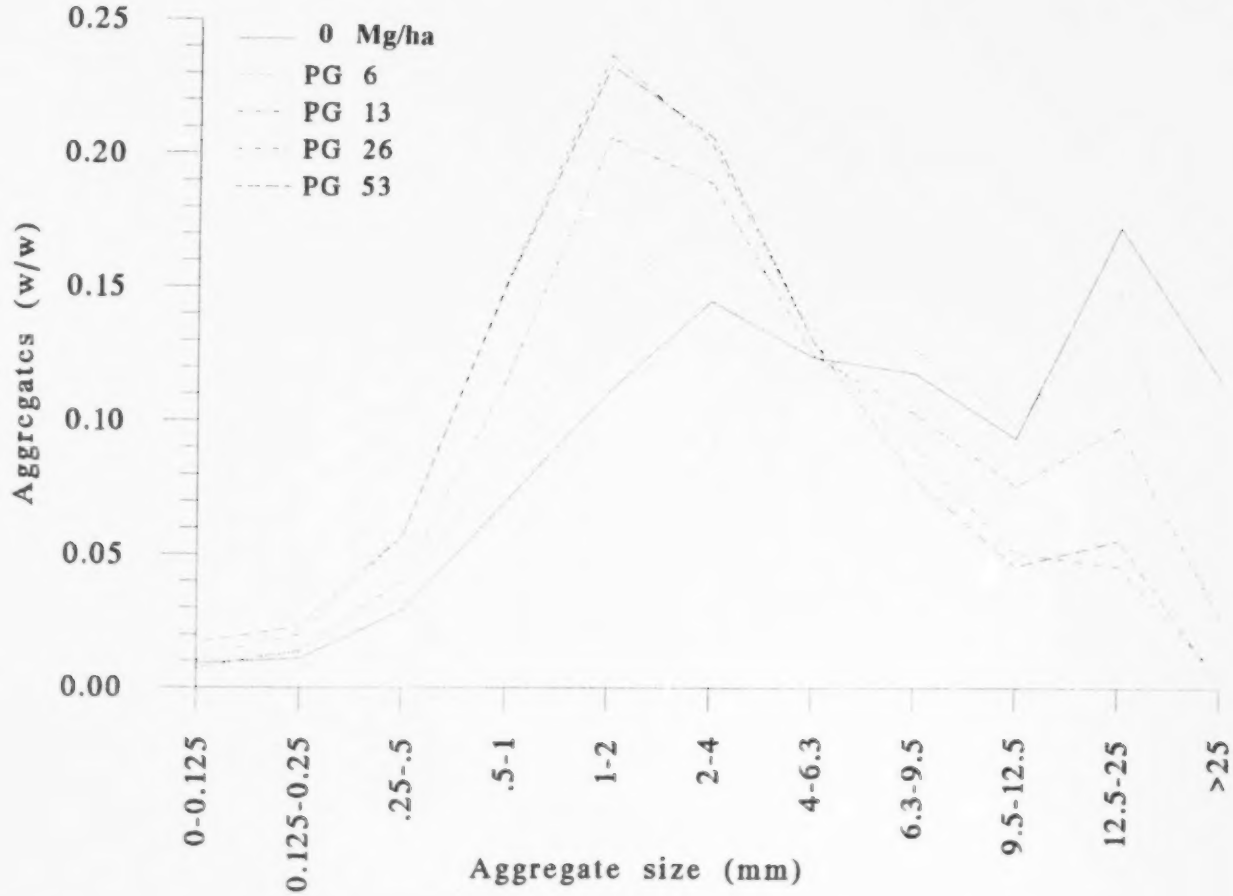

Figure 3.11a. Aggregate size distribution after dry-seiving of phosphogypsum-amended soils at Site 1 on August 7, 1991.

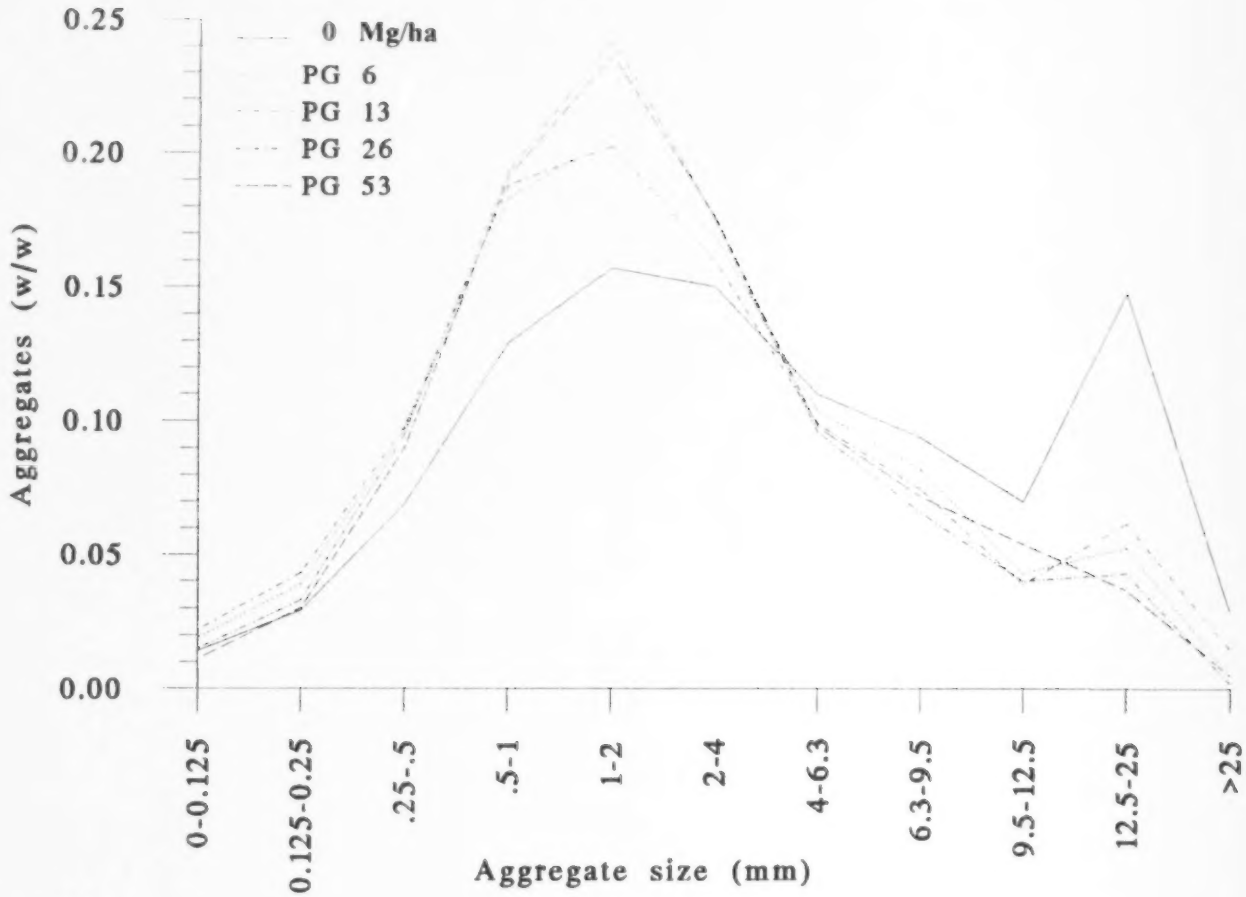

Figure 3.11b. Aggregate size distribution after dry-seiving of phosphogypsum-amended soils at Site 2 on August 7, 1991.

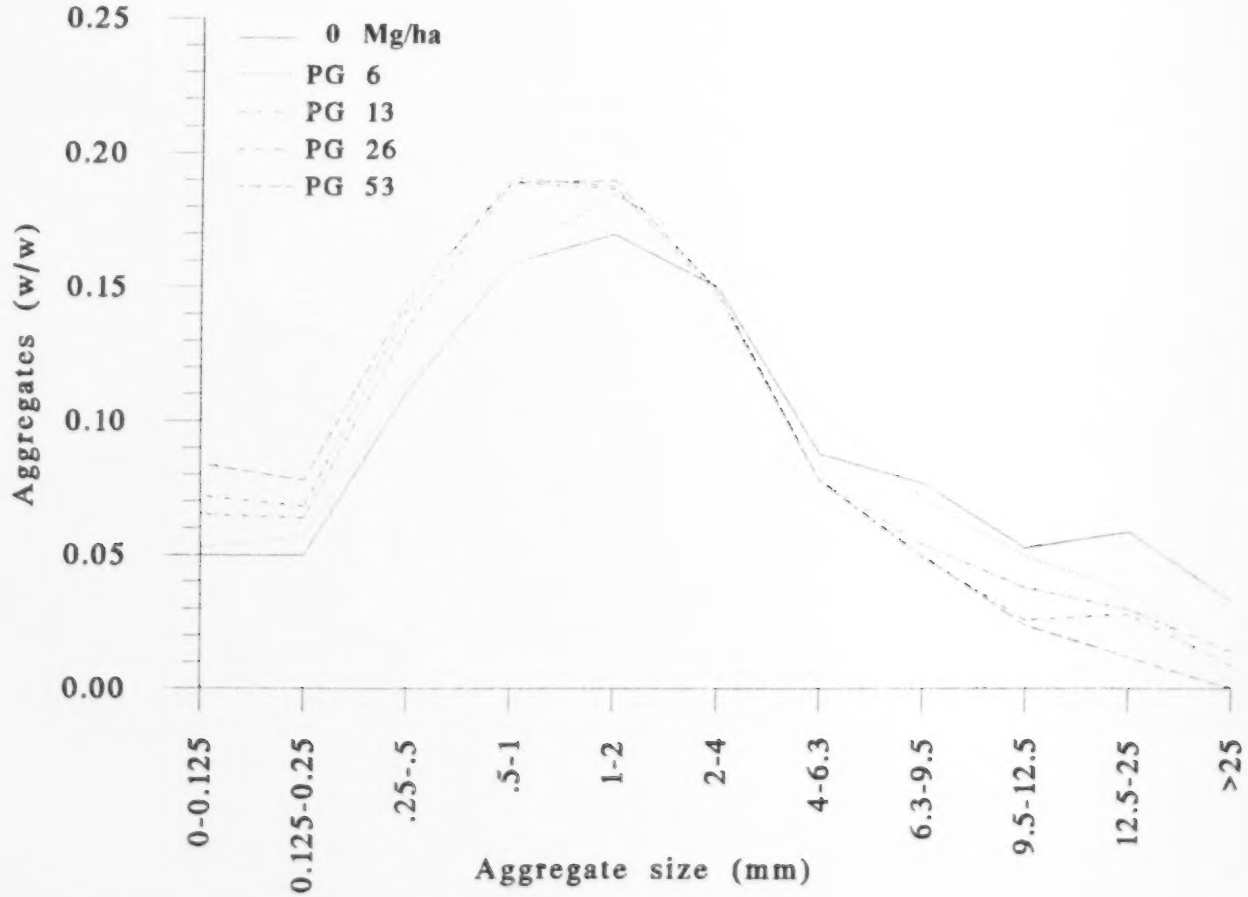

Figure 3.11c. Aggregate size distribution after dry-seiving of phopsphogypsum-amended soil at Site 3, September 3, 1991.

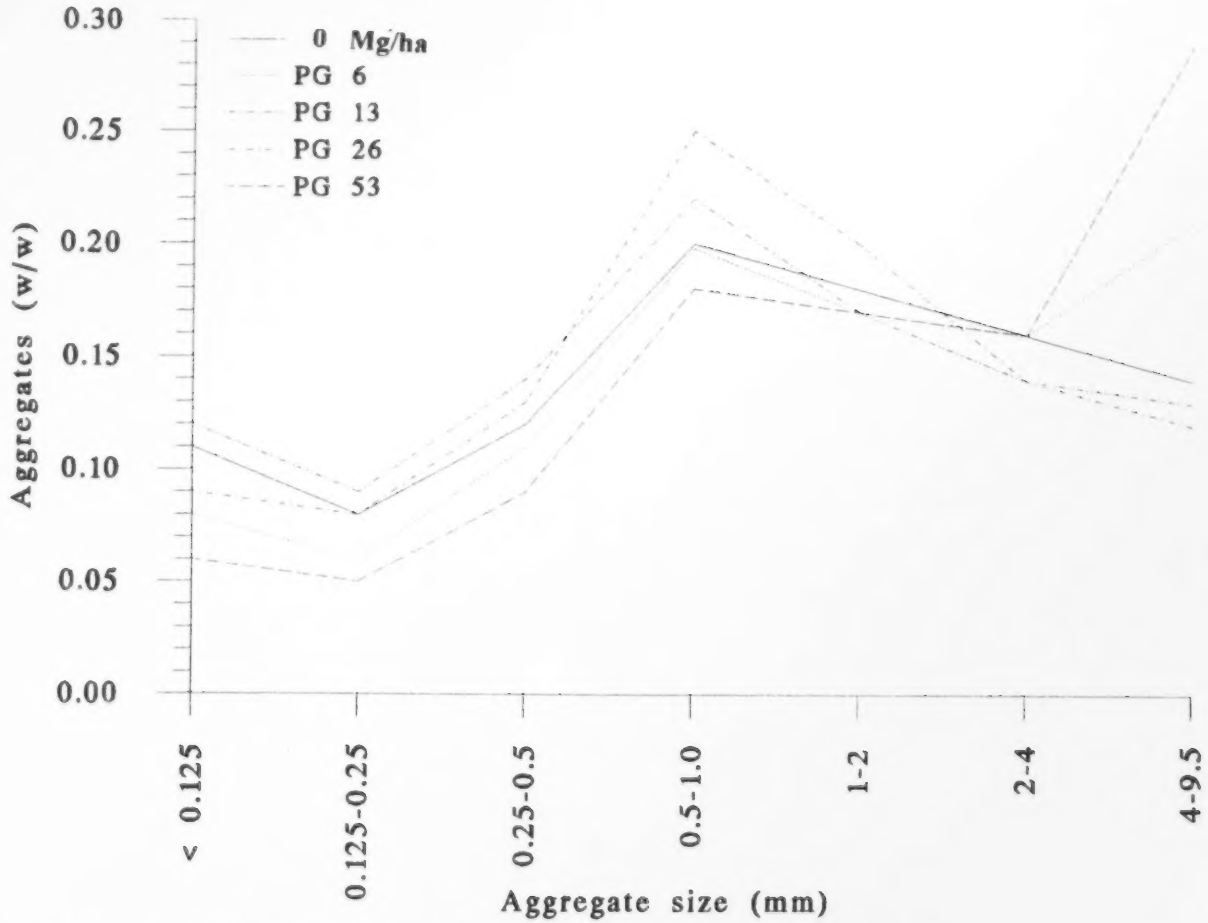

Figure 3.12a. Aggregate size distribution after wet-seiving of phopsphogypsum-amended soil at Site 1, October, 1991.

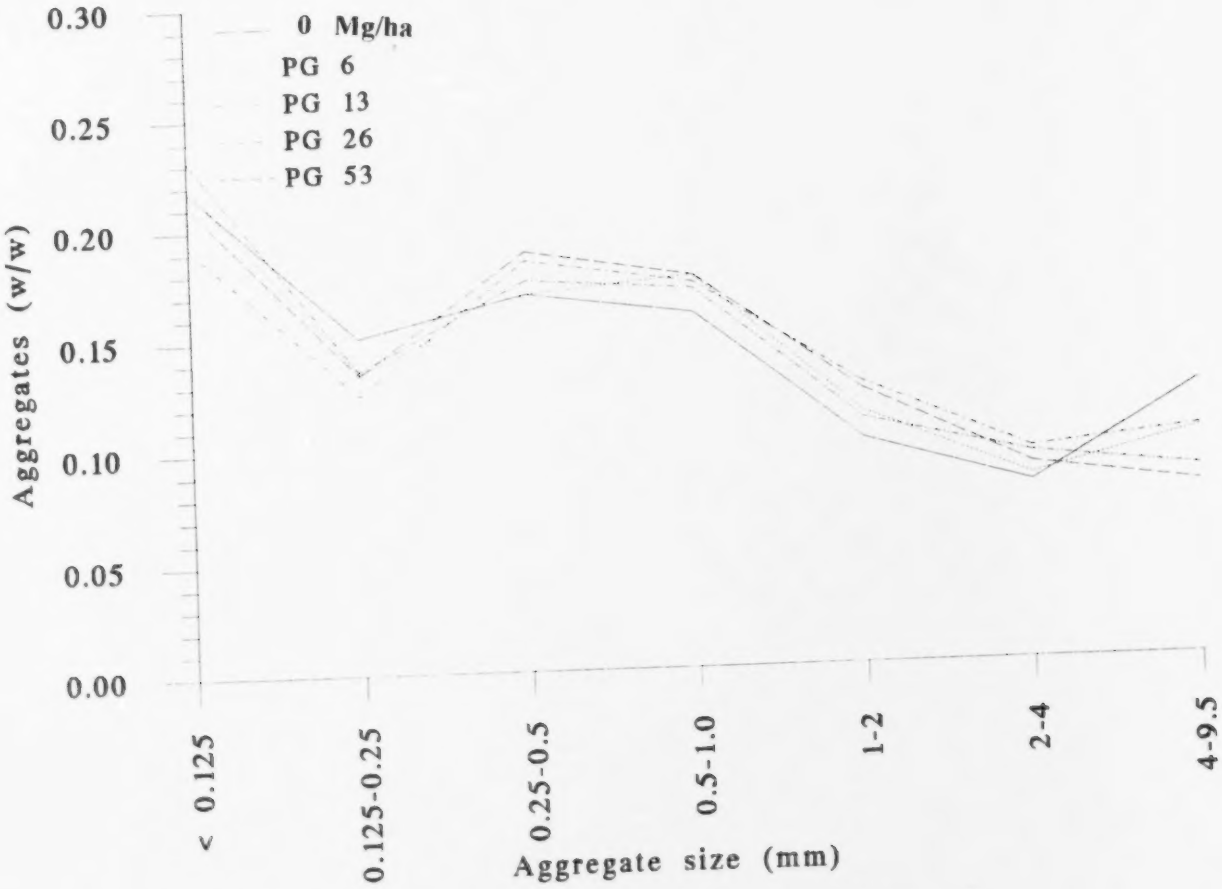

Figure 3.12b. Aggregate size distribution after wet-seiving of phosphogypsum-amended soil at Site 2, October, 1991.

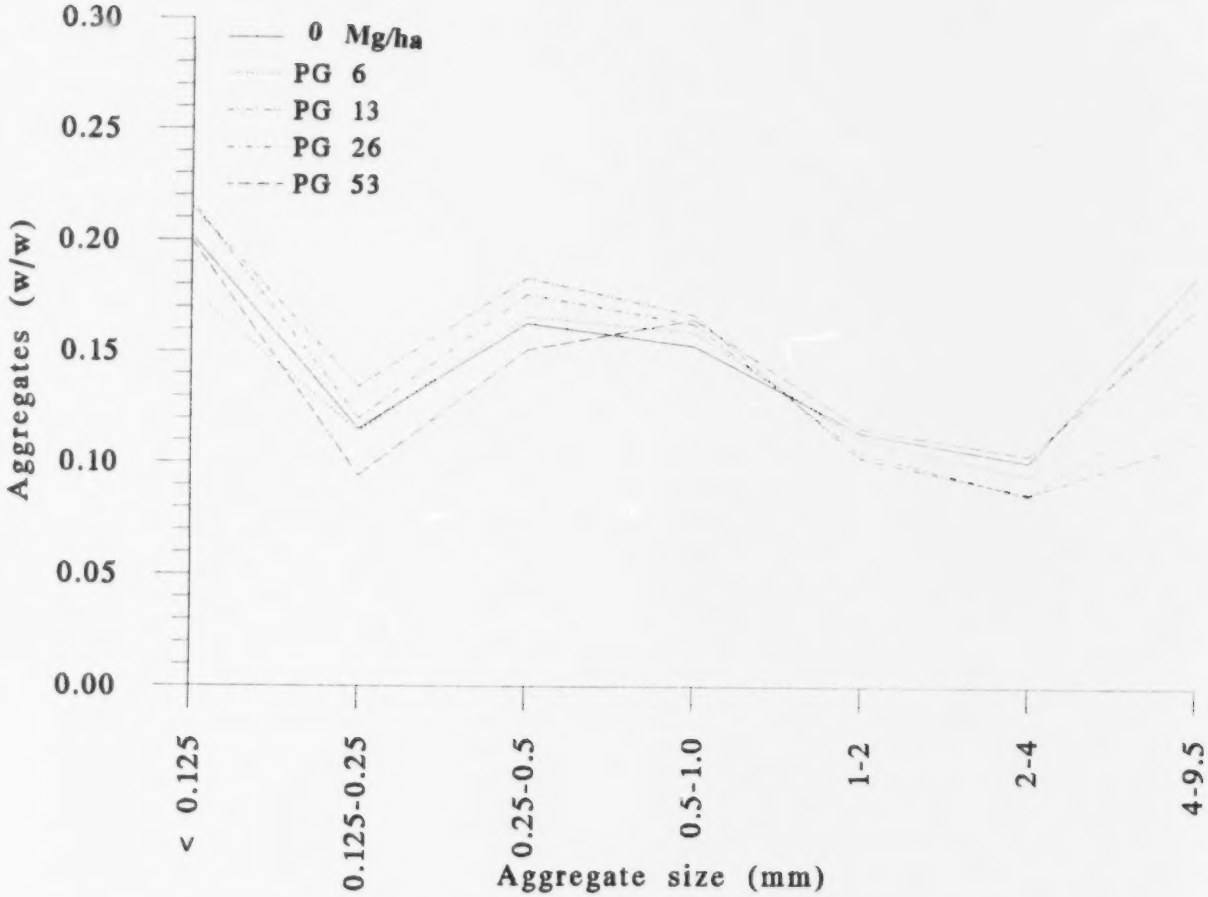

Figure 3.12c. Aggregate suze distribution after wet-seiving phopsphogypsum-amended soil at Site 3. October, 1991.

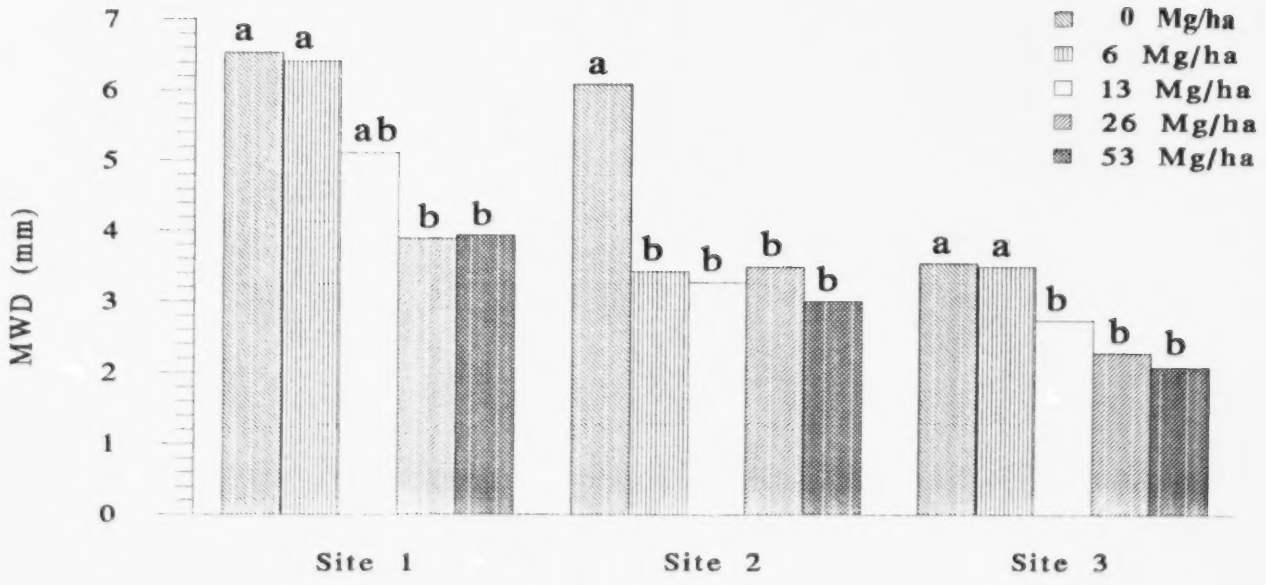

Figure 3.13a. Mean weight diameters (MWD) of dry-sieved, PG-amended, soil at Sites 1, 2 and 3. Letters within each site indicate significant differences by Duncan's Multiple Range Test at the 5% level.

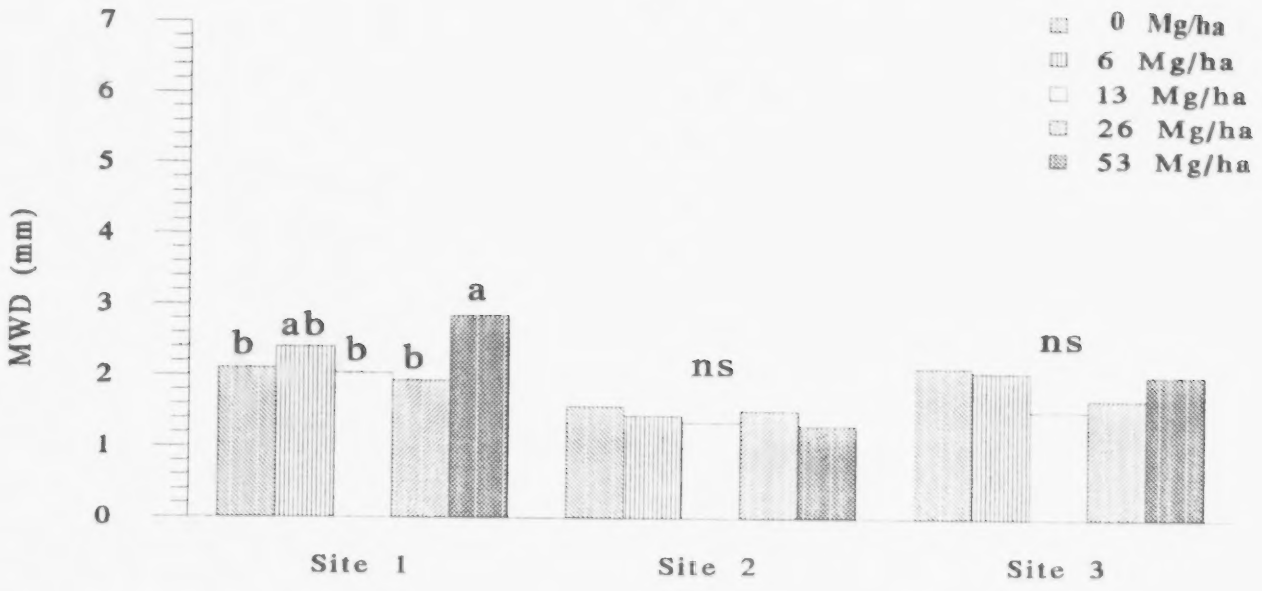

Figure 3.13b. Mean weight diameters (MWD) of wet-sieved, PG-amended, soil at Sites 1, 2 and 3. Letters within each site indicate significant differences by Duncan's Multiple Range Test at the 5% level, ns=not significant.

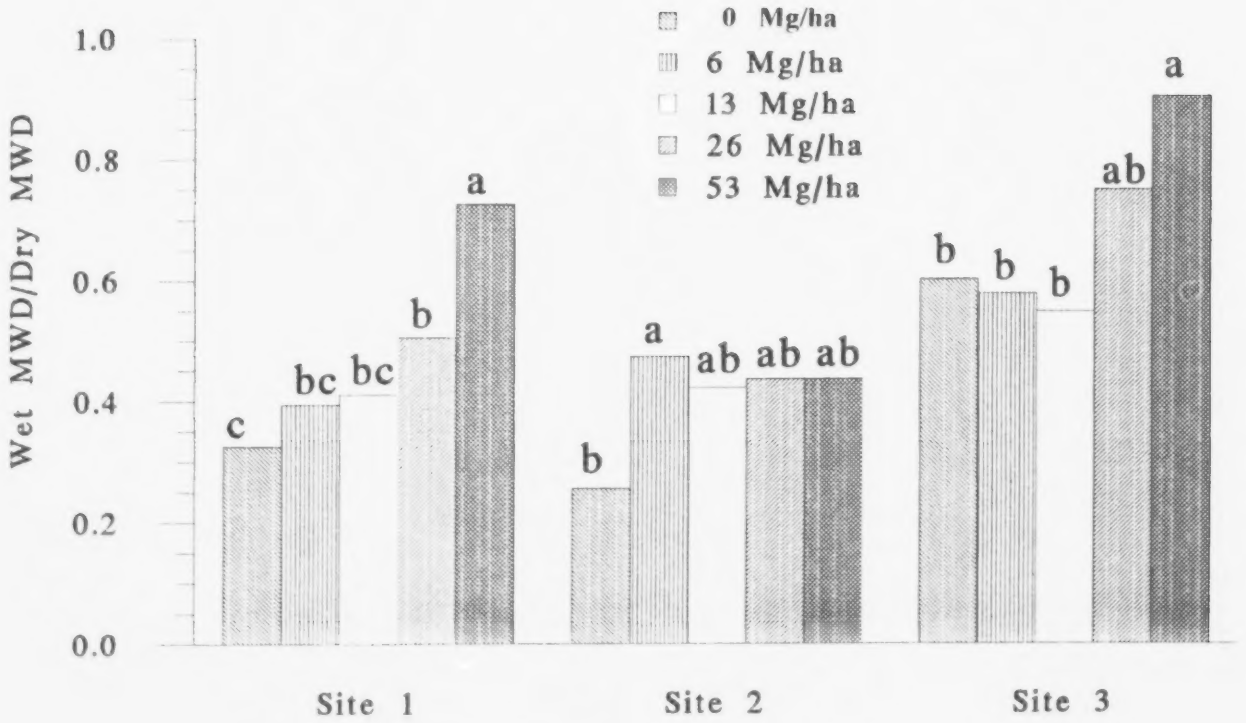

Figure 3.13c. Ratio of wet-seived MWD:dry-seived MWD in PG-amended soil at Site 1, 2 and 3. Letters within each site indicate significant differences by Duncan's Multiple Range Test at the 5 % level.

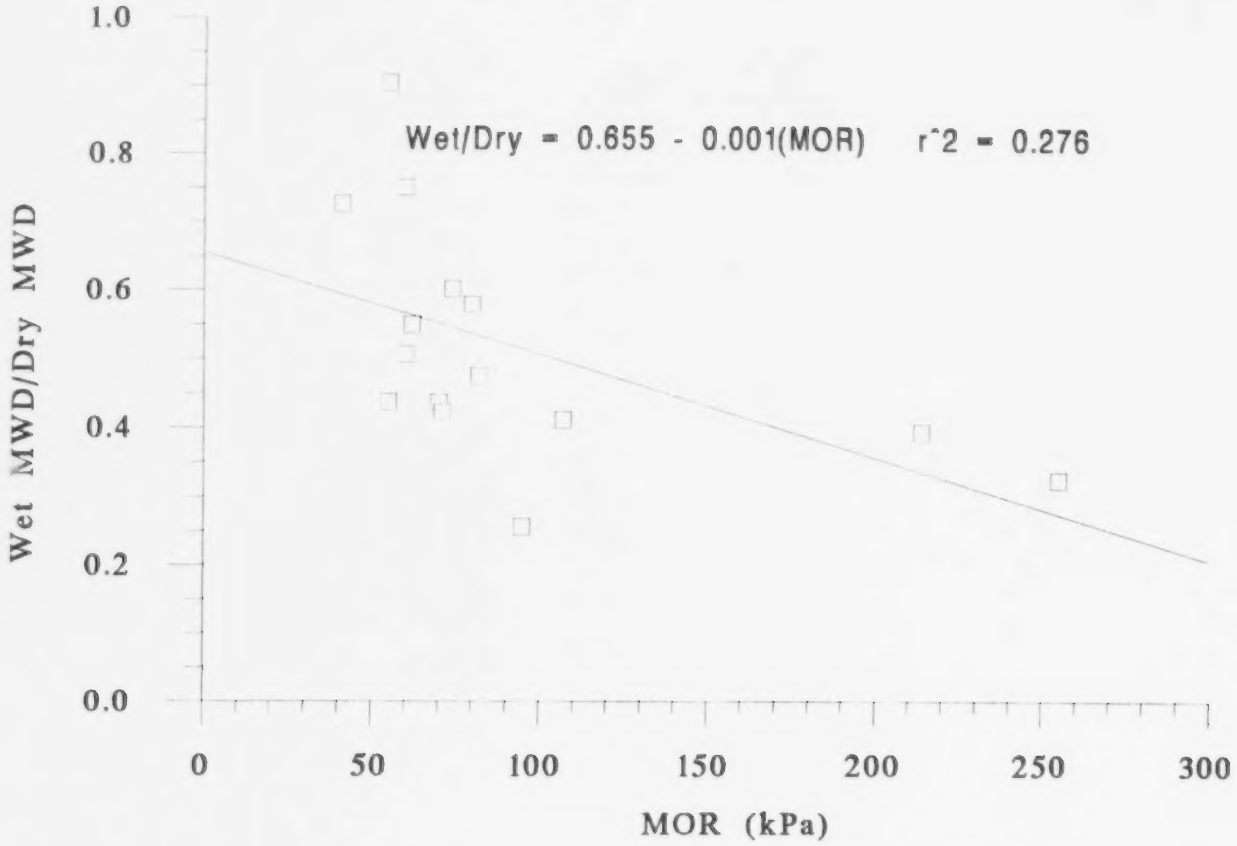

Figure 3.14 Relationship between MOR and the ratio of wet-seived MWD:dry-seived MWD in PG-amended soils. Includes means from Sites 1, 2 and 3.

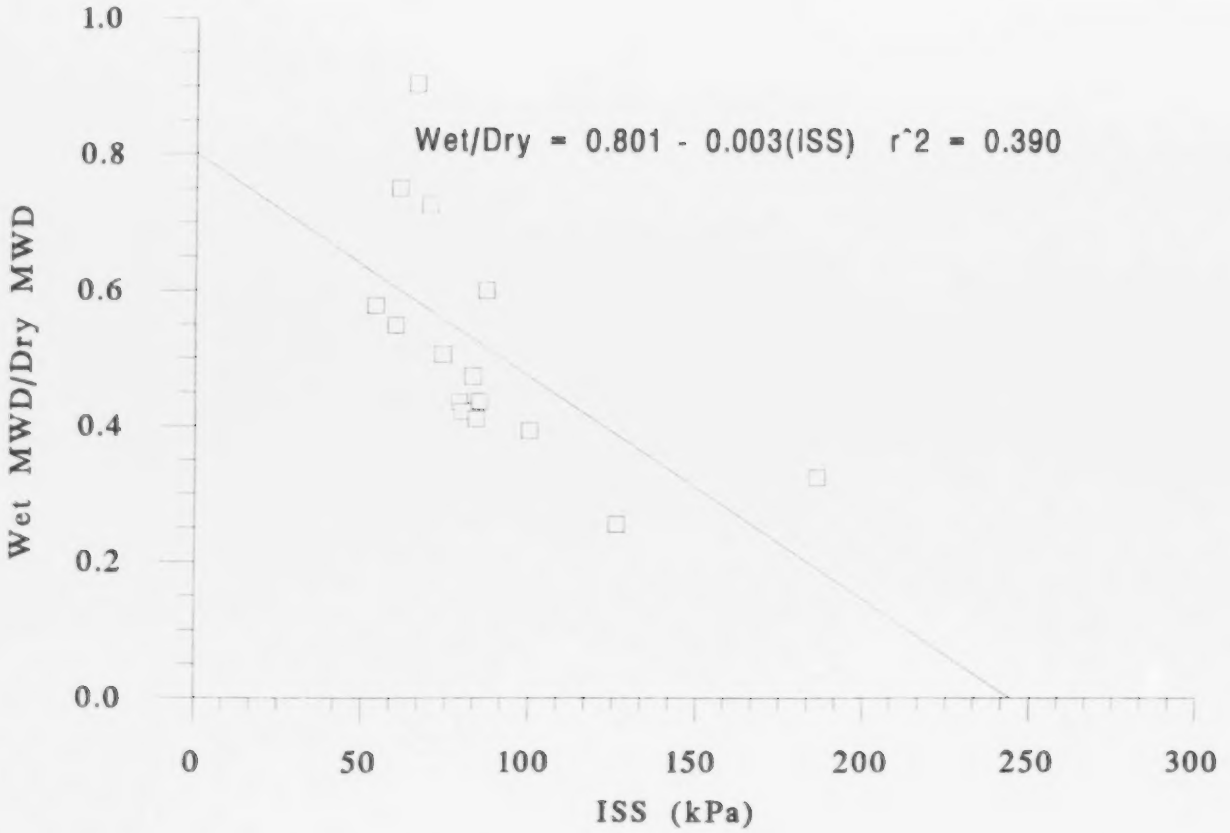

Figure 3.15 Relationship between In situ Surface Strength (ISS) and the ratio of wet-seived MWD:dry-seived MWD in PG-amended soils. Includes means from Sites 1, 2 and 3.

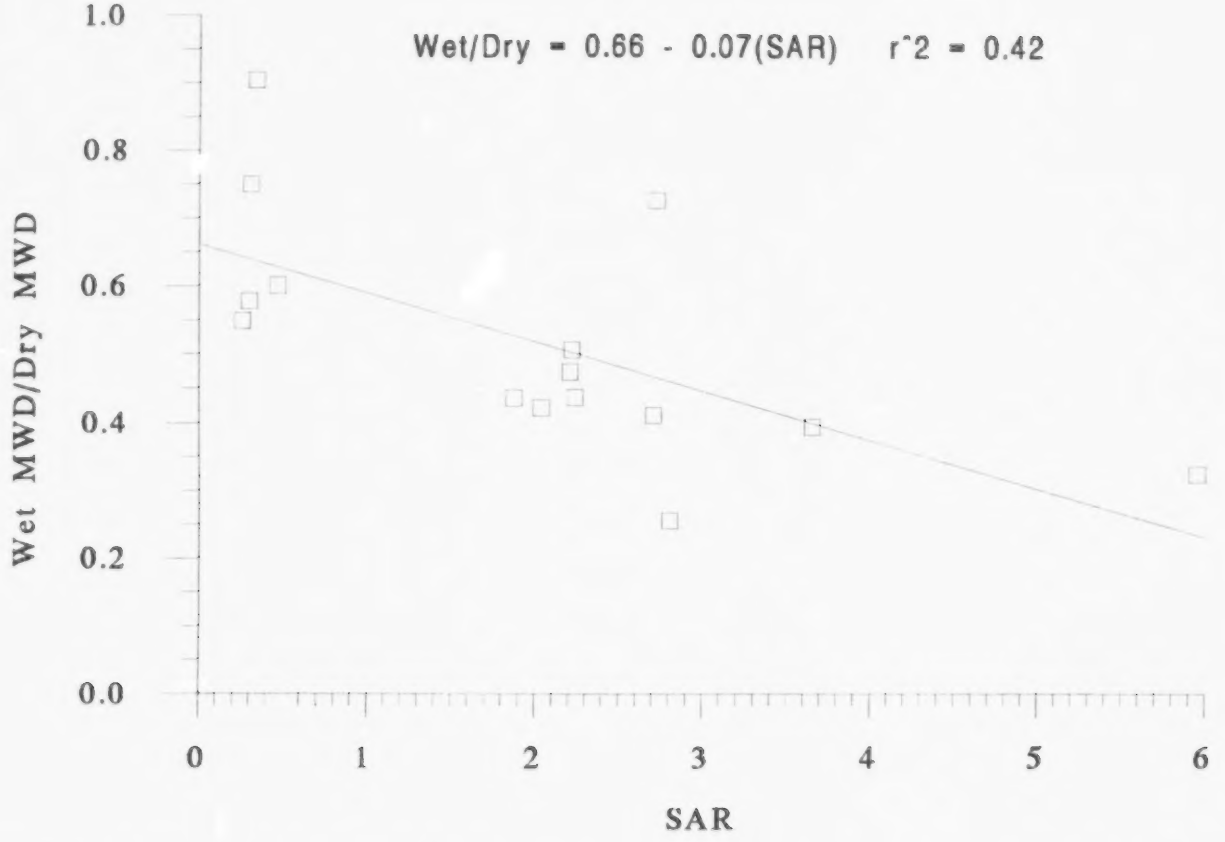

Figure 3.16 Relationship between the Sodium Adsorption Ratio (SAR) and the ratio of wet-seived MWD:dry-seived MWD in PG-amended soils. Includes means from Sites 1, 2 and 3.

Chapter 4. The Influence of Fly Ash on Selected Soil Tilth Parameters.

4.1 Chemical characteristics of fly ash-amended soil.

4.1.1 Introduction

The effects of Na and electrolyte concentration on soil quality, or tilth, have been well researched. Soils high in Na or those soils with low electrolyte concentrations are more susceptible to dispersion, resulting in the formation of surface crusts, reduced permeability and reduced aggregate stability. Reclamation of these saline/sodic soils involves the replacement of Na with Ca and increasing the electrolyte concentration of the soil pore water. As discussed in an earlier chapter, gypsum, or phosphogypsum, can be used to supply sufficient electrolyte concentrations and Ca for exchange with Na. Another material which may provide the same benefit is fly ash. The amount of fly ash required to reclaim these problem soils is dependent on the depth of soil to be reclaimed, amounts of Na present and the electrolyte concentration being sought as well as the chemical composition of the fly ash (FA).

Fly ash is an amorphous ferro-alumino silicate mineral, with the major matrix elements being Si, Al and Fe, together with significant percentages of Ca, K, Na, Mg and Ti (Sudhirendar et al., 1989). Fly ash obtained from the burning of bituminous coal, common to the Great Plains region, contains approximately 10% Ca and 2.48% Na (Dudas, 1981). Using columns of FA in leaching studies, Dudas (1981) found that the Ca contained in FA was much more readily dissolved than Na. Thus, FA could potentially be used as a soil amendment when reclaiming highly dispersive soils.

Fly ash has been recorded tc have a neutralizing capacity 20 % that of agricultural limestone, making it an excellent liming material for acidic soils (Sudhirendar et al., 1989). Coal ash has a high concrentration of Ca and Mg oxides, which when hydrolyzed, will increase soil pH. Other studies have observed that FA additions might increase soil pH to neutrality in the initial stages, but additional applications may be required in later years to neutralize the soil's reserve acidity (Adams et al., 1972; Sudhirendar et al., 1989).

Fly ash has also been observed to induce salinity with fresh, unweathered, ash causing greater salinity than weathered FA (Page et al.,1979; Sudhiredar et al., 1989). Adriano et al. (1978) observed FA addition increased electrical conductivity (EC) of the soil solution to the extent that it reduced crop growth. Application of FA in large amounts may increase soil EC to unsuitable levels, but if appropriate amounts are applied, an increase in EC may be useful in reclaiming highly dispersive soils.

Objectives of this study were to (1) determine the effect of various rates of FA application on the soil solution chemistry of naturally formed soils and soils reclaimed from the strip mining of coal and (2) to determine which rate of FA application is most beneficial in the improvement of soil tilth.

4.1.2 Materials and Methods

Please refer to Section 2.3.

4.1.3 Results and Discussion

4.1.3.i Soluble cations in soil paste extracts

At Site 1 the amount of soluble Ca in the 0-10 cm interval increased from 1.6 to 2.2 mmol L^{-1} with the addition of 6 Mg ha^{-1} of FA (Table 4.1a). Further increases in soluble Ca were not observed with increased rates of FA addition in the 0-10 cm interval. Soluble Ca in the 10-25 cm soil layer increased more than threefold with the addition of 26 Mg ha^{-1} FA. Relatively large increases in soluble Ca were observed with other rates of application, but due to site or sampling variability, these increases were not statistically significant.

Increases in soluble Ca, due to FA addition, were observed in the 0-10 cm layer at Site 2 (Table 4.1b). Soluble Ca increased from 4.4 mmol L^{-1} in the 0 Mg ha^{-1} rate, to 13 mmol L^{-1} for the 53 Mg ha^{-1} rate. Only the 26 and 53 Mg ha^{-1} rates of FA increased

soluble Ca significantly. No significant changes in Ca were measured in the 10-25 cm depth interval at Site 2.

Levels of soluble Ca in the 0-10 cm depth interval at Site 3 increased with the application of FA even at the lowest rate of addition, but seemed to stabilize at rates greater than 26 Mg ha^{-1} (Table 4.1c). In the 10-25 cm layer, increases in Ca were observed with the addition of FA at rates of 26 and 53 Mg ha^{-1}. At both depth intervals, differences among rates were not statistically significant.

Slight increases in soluble Ca are due to the soluble Ca content of FA. The highest rate of FA application corresponds to only 5% of the mass of the 0-10 soil depth interval, possibly explaining the insignificant or slight increases in soluble Ca. At Site 1, the largest increase in soluble Ca occurred in the 10-25 cm depth interval. When FA was applied to this site, soil tilth was extremely poor due to the presence of large clods at the soil surface, some in excess of 15 cm in diameter. Due to a rotary tillage operation to incorporate the FA into the upper 10 cm of the soil surface, a large amount of the FA may have settled to the bottom of the zone of tillage, thus resulting in a larger increase in Ca in the 10-25 cm zone. Surface soil tilth at Site 3 prior to FA addition was much better than that at Site 1 due to the granular soil structure in the Ap horizon, thus allowing for a more thorough mixing of FA into the 0-10 cm depth interval. As a consequence, at Site 3 there was almost no enrichment of Ca in the 10-25 cm zone compared to the 0-10 cm zone. At Site 2, however, the level of Ca in the 0-10 cm interval increased more than two-fold with the addition of 26 and 53 Mg ha^{-1} FA. Some of the increase in Ca may be attributed to surface runoff from adjacent PG-amended plots. This site was not level, with the north plots being higher than those at the south end. Although the treatment layout was random, many of the FA-treated areas are on the southern, down-slope portion of the site (see Figure 2.4). With spring snowmelt and some intense rainfall events, these FA-treated areas may have received some runoff from upslope PG-treated areas.

The earth was made so various that the mind of desultory man, studious of change and pleased with novelty, might be indulged.

William Cowper
The Task, 1780

4.1.4 Conclusions

Addition of fly ash, even at rates of up to 53 Mg ha^{-1}, did not significantly change the levels of soluble Ca, Mg and Na, thus resulting in no changes in the electrical conductivity nor in the SAR of the FA-amended soils. Fly ash was generally effective in increasing the soil pH of the 0-10 cm depth at all sites, with the most dramatic increases occurring in those soils with initially low soil pH. To effectively reclaim Sites 1 and 2 from a salinity/sodicity point of view, much higher rates of FA would be necessary in order to supply enough readily soluble Ca for exchange with Na and to increase the electrolyte concentration. Rates as low as 26 Mg ha^{-1} may be sufficient to reclaim soils from a soil pH point of view. As observed at Site 3, FA increased soil pH towards neutrality. However such increases in pH could have significant positive effects on the nitrogen-fixing potential of leguminous forage crops and overall crop growth in acidic soils. These results were recorded 16 months after the date of application, therefore, the longevity of the effect of FA on soil pH has yet to be determined.

Table 4.1a. Chemical characteristics of FA-amended soil at Site 1.

Application rate (Mg ha-1)	pH (water)	EC (dS m^{-1})	Soluble cations (mmol L^{-1}) Ca	Mg	Na	SAR
			0-10 cm depth interval			
0	7.5 bc*	1.1	1.6	0.7	9.1	6.0
6	7.6 abc	1.2	2.2	0.9	8.7	5.0
13	7.2 c	1.2 ns	2.1 ns	0.9 ns	8.3 ns	4.8 ns
26	8.1 a	1.3	2.3	0.8	9.8	4.4
53	8.0 ab	1.2	2.3	0.8	8.2	4.6
			0-25 cm depth interval			
0	7.5	2.1	2.9	1.1	16	8.7
6	7.5	2.1	4.4	0.9	17	9.3
13	7.1 ns	1.5 ns	8.1 ns	0.7 ns	12 ns	7.7 ns
26	7.4	2.7	9.9	1.5	21	9.4
53	7.4	2.3	7.4	2.4	16	7.2

*individual treatment means within a column for a given depth interval followed by the same letter are not significantly different as determined by DMR ($P<0.05$), ns=not significant

Table 4.1b. Chemical characteristics of FA-amended soil at Site 2.

Application rate (Mg ha^{-1})	pH (water)	EC (dS m^{-1})	Soluble cations (mmol L^{-1}) Ca	Mg	Na	SAR
			0-10 cm depth interval			
0	6.0 d*	1.8 b	4.4 b	2.2 b	7.1	2.8
6	6.3 cd	1.8 b	5.2 b	2.4 b	7.1	2.7
13	6.6 bc	1.7 b	4.8 b	2.2 b	6.9 ns	2.6 ns
26	6.7 b	3.0 ab	10 a	3.9 ab	8.7	2.3
53	7.4 a	3.5 a	13a	4.3 a	11	2.6
			10-25 cm depth interval			
0	6.9	1.2	3.2	1.2	6.2	3.0
6	6.5	1.0	1.9	0.9	5.4	3.3
13	6.8 ns	2.0 ns	1.9 ns	1.8 ns	11 ns	5.6 ns
26	7.0	1.2	2.8	1.2	5.4	2.7
53	6.8	1.3	3.1	1.3	6.1	2.8

*individual treatment means within a column for a given depth followed by the same letter are not significantly different as determined by DMR ($P<0.05$), ns=not significant

Table 2.2c Chemical characteristics of FA-amended soil at Site 3.

Application rate (Mg ha^{-1})	pH (water)	EC (dS m^{-1})	Soluble cations (mmol L^{-1}) Ca	Mg	Na	SAR
		0-10 cm depth interval				
0	5.7 d*	1.7	6.1	2.5	1.4	0.47
6	5.9 c	2.1	8.2	3.0	1.4	0.44
13	6.3 b	1.8 ns	6.5 ns	2.5 ns	1.5 ns	0.50 ns
26	6.6 b	2.4	9.4	3.2	2.0	0.59
53	7.2 a	2.4	9.7	2.9	1.8	0.52
		10-25 cm depth interval				
0	5.9	0.58	1.6	0.8	1.3	0.82
6	5.9	0.59	1.5	0.8	1.4	0.95
13	6.0 ns	0.62 ns	1.6 ns	0.8 ns	1.2 ns	0.77 ns
26	6.0	0.70	2.0	0.9	1.3	0.76
53	5.9	0.82	2.3	1.0	1.2	0.69

*individual treatment means within a column for a given depth followed by the same letter are not significantly different as determined by DMR ($P<0.05$), ns=not significant.

4.1.5 References

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4.2 Influence of fly ash on soil surface strength

4.2.1 Introduction

Please refer to Section 3.2.1.

As discussed in Section 4.1, materials which could provide sufficient electrolytes to soil water and Ca for exchange with Na would be beneficial to the stability of soil aggregates and in preventing the formation of surface crusts. Fly ash, containing appreciable amounts of readily soluble Ca, may be one such material which could be used to reduce the soil crusting potential of soils.

The objectives of this study were to determine the effects of FA, applied at various rates, on soil surface strength *in situ* and in the laboratory.

4.2.2 Materials and Methods

Please refer to Section 2.3.

4.2.3 Results and Discussion

At Site 1 the addition of FA decreased the *in situ* surface strength (ISS) on two measurement dates (Figure 4.1a). ISS measured on August 19 was not significantly different from the 0 Mg ha^{-1} rate. Significant results occurred, however, on September 3 and 25, 1991. On September 3, ISS decreased, significantly, from 241 kPa in the 0 Mg ha^{-1} rate to 142 and 119 kPa for the 26 and 53 Mg ha^{-1} application rates, respectively. ISS for all rates of application was significantly different from that in the 0 Mg ha^{-1} rate on September 25, with no significant differences among the 6, 13, 26 and 53 Mg ha^{-1} rates. Surface soil moisture at the time of ISS measurements was not significantly different.

There were no significant differences in ISS at Site 2 on September 3 (Figure 4.1b). On September 25, however, significant differences in ISS were observed between the 0 Mg ha^{-1} rate and all other rates of applied FA. ISS decreased from 134 kPa in the 0

Mg ha^{-1} rate to 86, 92, 79 and 95 kPa in the 6, 13, 26 and 53 Mg ha^{-1} rates of FA, respectively. No significant differences in ISS were observed among the 6, 13, 26 and 53 Mg ha^{-1} rates. Surface soil moisture at the time of ISS measurements was not significantly different among treatments.

At Site 3 all rates of FA application decreased ISS, but only a few were significant (Figure 4.1c). On September 10, 1991, ISS of 78 kPa in the 0 Mg ha^{-1} rate decreased siginificantly to 54 kPa in the 13 Mg ha^{-1} rate of application. On September 25, 1991, ISS in the 0 Mg ha^{-1} rate was 96 kPa while the ISS for the 13 and 53 Mg ha^{-1} rates were significantly lower at 72 and 66 kPa, respectively. Soil surface moisture was not significantly different among the 6, 13, 26 and 53 Mg ha^{-1} rates on September 25, but the 26 Mg ha^{-1} rate of FA (15.6 g/g x 100) application had a significantly higher soil moisture content than the 0 Mg ha^{-1} rate (13.4 %) on September 10.

The modulus of rupture (MOR) of surface soil samples taken from all sites decreased with the application of FA, but much like the ISS measurements not all changes in MOR were statistically siginficant. At Site 1, only the 53 Mg ha^{-1} rate of FA decreased the MOR significantly compared to the 0 Mg ha^{-1} rate (Figure 4.2a). However, the MOR of the 13, 26 and 53 Mg ha^{-1} rates differed significantly from the 6 Mg ha^{-1} rate of FA application. MOR values from Site 1 were 254, 325, 161, 176 and 79 kPa in the 0 Mg ha^{-1} rate, 6, 13, 26 and 53 Mg ha^{-1} application rates, respectively. At Site 2 the MOR decreased significantly from 95 kPa in the 0 Mg ha^{-1} rate to 53 and 55 kPa in the 26 and 53 Mg ha^{-1} rates, respectively (Figure 4.2b). The MOR at Site 3 behaved similarly to the ISS measurements of September 25 (Figure 4.2c), where the ISS for the 13 (48 kPa) and 53 Mg ha^{-1} (43 kPa) rates of FA were significantly lower than that for the 0 Mg ha^{-1} rate (74 kPa).

MOR of each site was plotted with the date-averaged ISS values for each of the corresponding three sites (Figures 4.2a, b and c). The results of the two methods for determining soil surface strengths are fairly comparable. A simple correlation between

MOR and ISS resulted in an r^2 value of 0.50 (Figure 4.3). An r^2 of 0.26 or higher signifies a significant correlation at the 5 % level. Measuring soil surface strength *in situ* is quite comparable to the modulus of rupture technique, but *in situ* measurements can be done much more quickly and without bringing soil samples into the lab; thus, ISS measurements may be more favourable in a field situation than MOR determinations.

4.2.4 Conclusions

The most dramatic decreases in soil surface strength, using the ISS and MOR methods, occurred at the highest rates of FA addition and at Site 1 which had the highest clay content and poorest initial tilth conditions. Decreases in surface strength were also observed at Sites 2 and 3, but the differences between controls and FA-amended areas were not as large, possibly due to lower clay contents and/or better initial tilth conditions. As discussed in Section 4.1, no significant changes in the soil chemistry of the 0-10 cm interval were observed (with the exception of Site 2). Therefore changes in surface strength may not be attributed to increases in electrolyte content or the exchange of Ca for Na. The physical presence of FA may have had an effect in physically interfering with the cohesiveness of soil particles, thus reducing crust strength, especially in soils with high clay contents.

Considering MOR in relation to seedling emergence data of previous research, it cou'd be suggested that for cereal and small seeded crops, a limiting *in situ* crust strength could be set at 100 kPa (Allison and Moore, 1956, set the critical modulus of rupture for corn at 120 kPa). In areas with similar conditions to Site 1, rates of FA needed to decrease crust strength values to below 100 kPa would be in excess of 53 Mg of FA ha^{-1}. Rates of approximately 26 Mg ha^{-1} may be sufficient for Site 2. At Site 3 crust strengths were already below 100 kPa at the 0 Mg ha^{-1} rate, therefore the application of FA at this site was not needed for reducing surface crusting potential.

4.2.5 References

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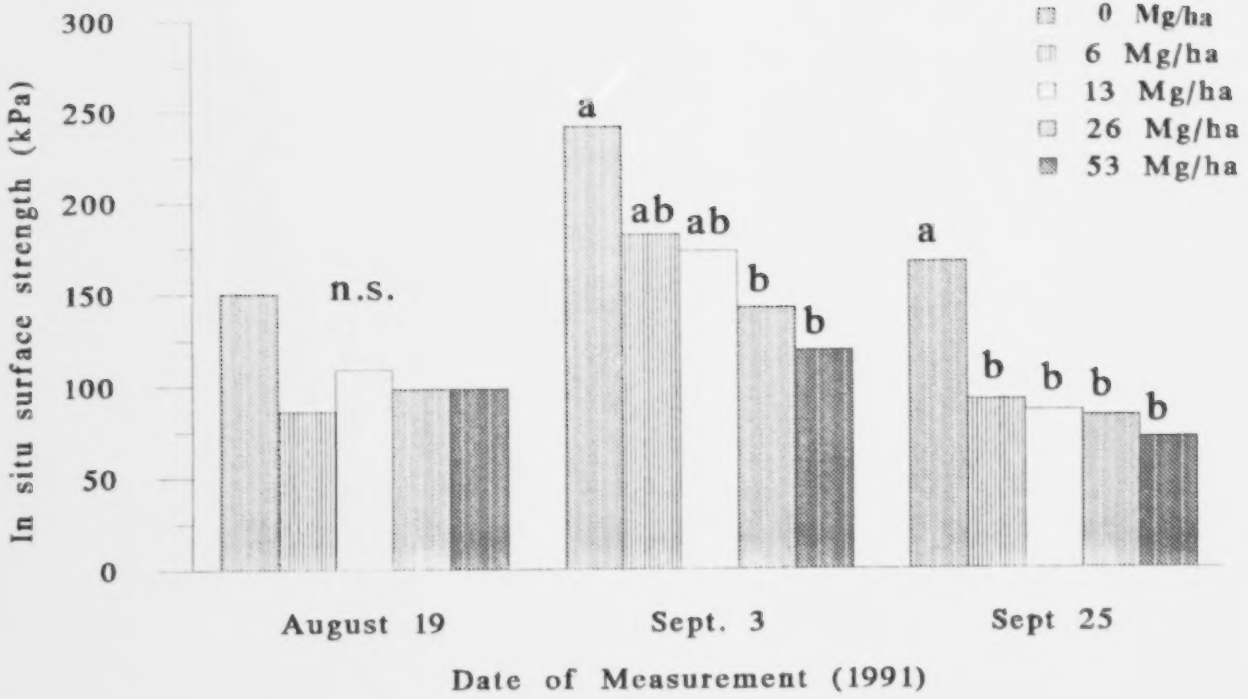

Figure 4.1a. In situ surface strength at Site 1. Letters within each date indicate significant differences by Duncan's Multiple Range Tests at the 5% level, ns=not significant.

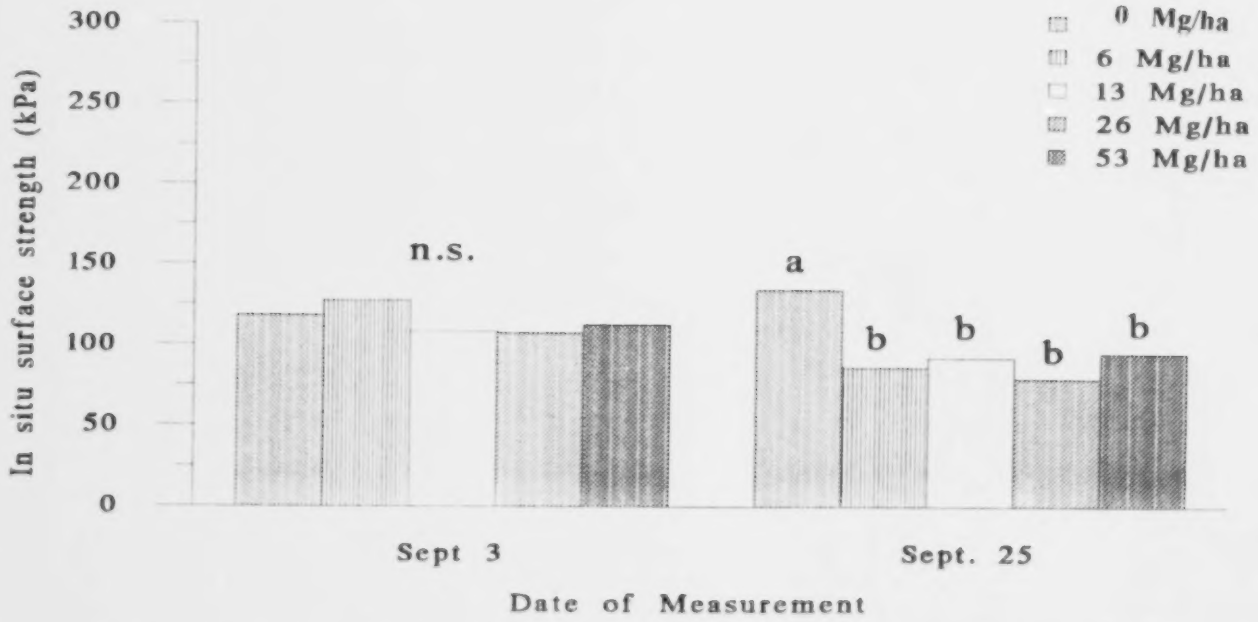

Figure 4.1b In situ surface strength at Site 2. Letters within each date indicate significant differences by Duncan's Multiple Range Test at the 5% level, ns=not significant.

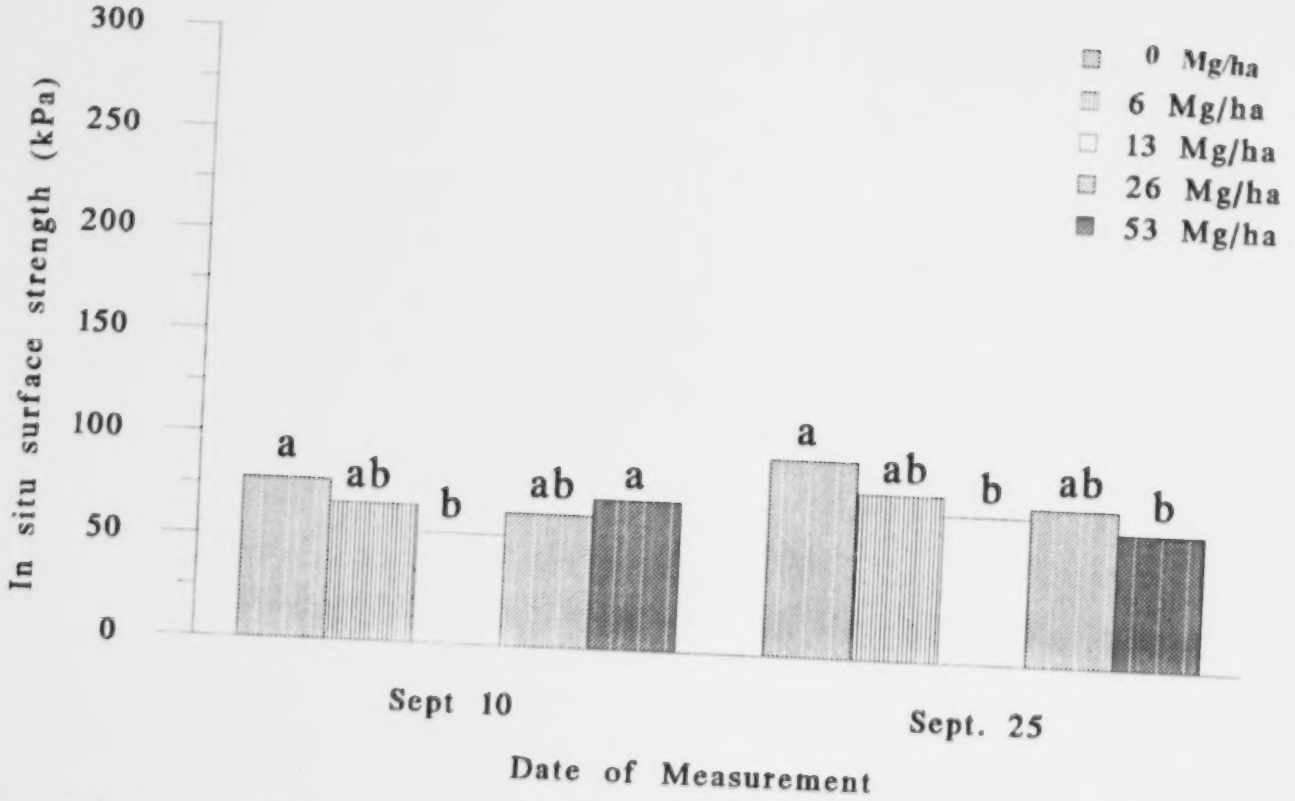

Figure 4.1c In situ surface strength at Site 3. Letters within each date indicate significant differences by Duncan's Multiple Range Test at the 5% level.

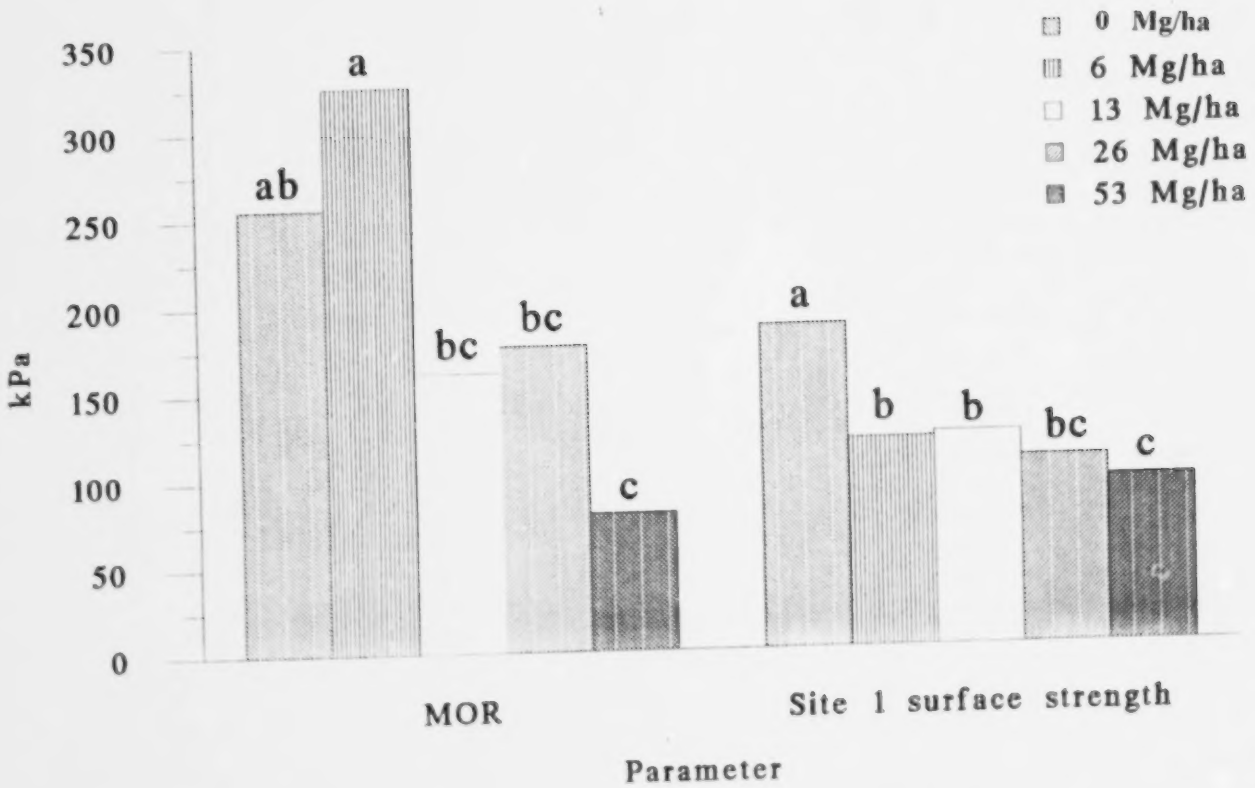

Figure 4.2a. Modulus of rupture (MOR) and date averaged in situ surface strength of FA-amended soil at Site 1. Letters indicate significant differences by Duncan's Multiple Range Test at the 5% level.

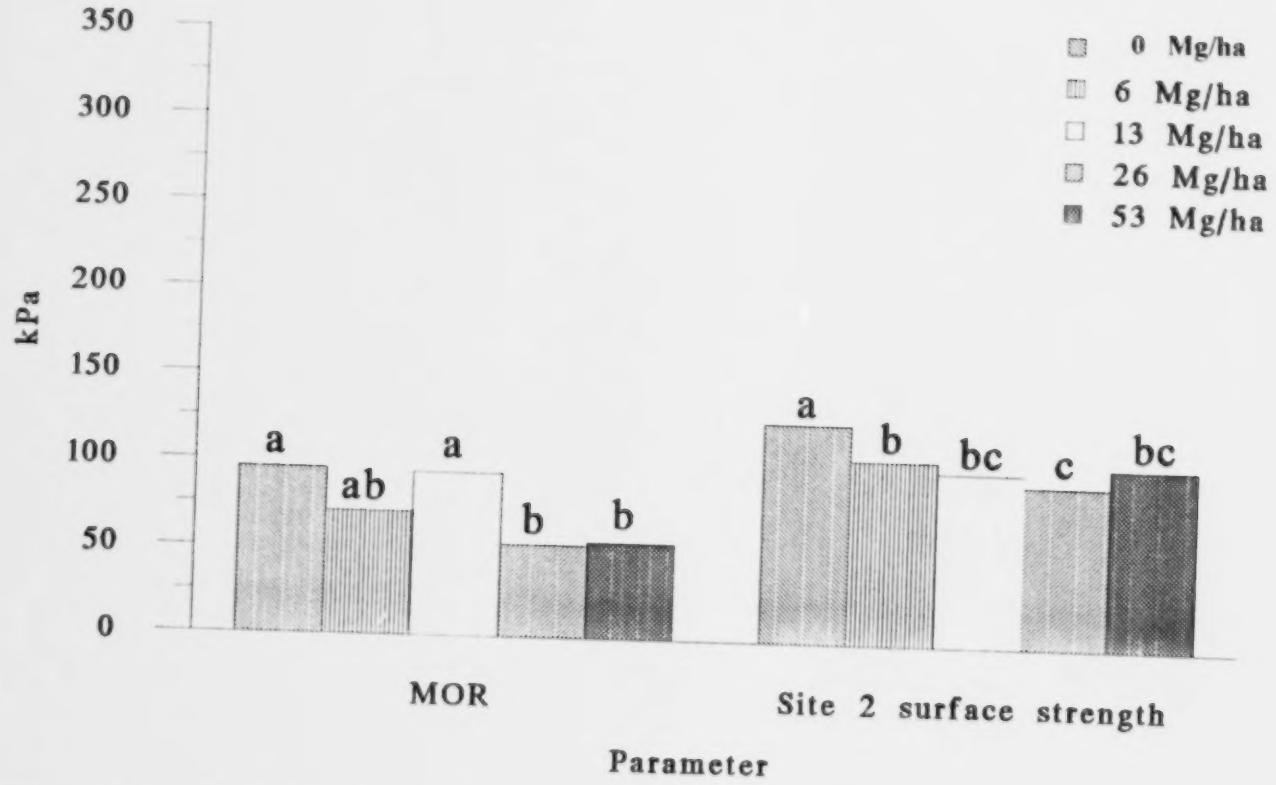

Figure 4.2b. Modulus of rupture (MOR) and date averaged in situ surface strength at Site 2. Letters indicate significant differences by Duncan's Multiple Range Test at the 5% level.

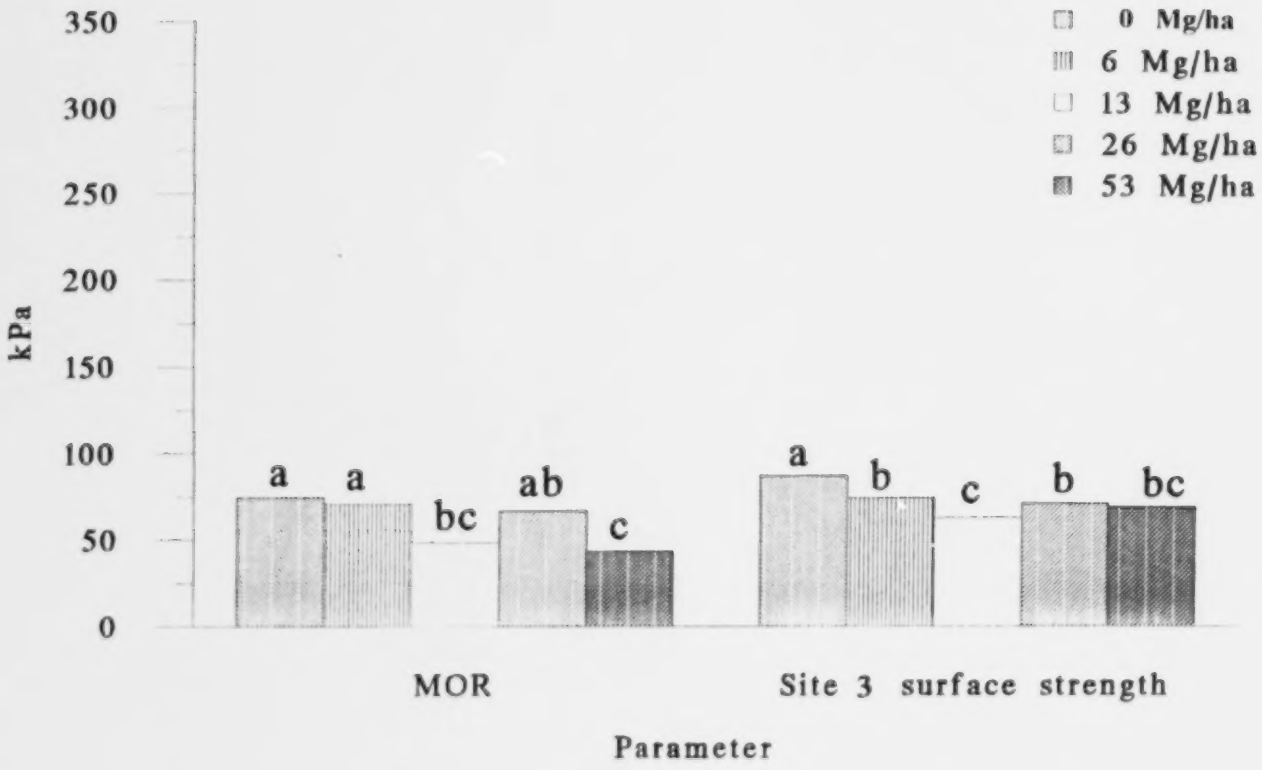

Figure 4.2c. Modulus of rupture (MOR) and date-averaged in situ surface strength at Site 3. Letters indicate significant differences by Duncan's Multiple Range Test at the 5% level.

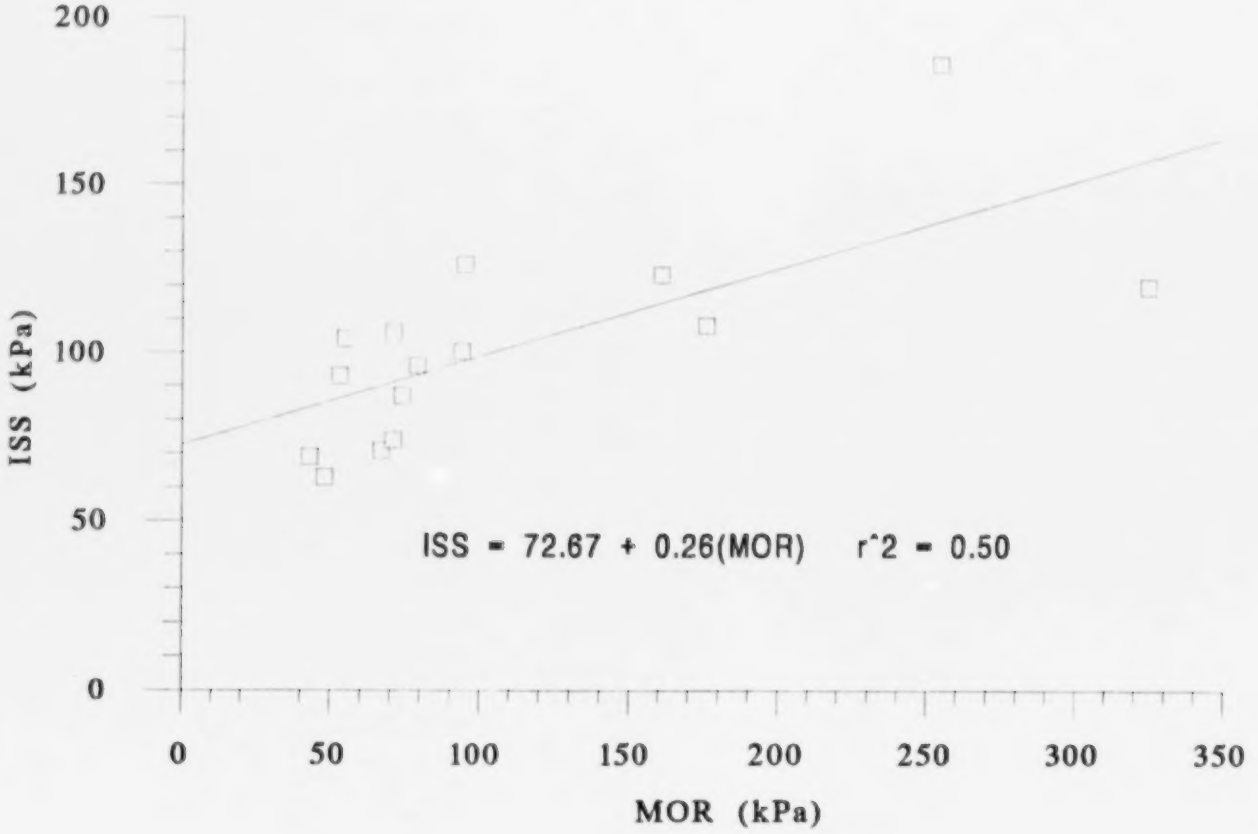

Figure 4.3 Relationship between MOR and ISS means, from Sites 1, 2 and 3, in FA-amended soils.

4.3 The size distribution and stability of aggregates in fly ash-amended soil.

4.3.1 Introduction

Please refer to section 3.3.1

Use of calcium-containing products, such as lime, gypsum, gypsum by-products or fly ash can be used to improve the structural stability of soils, especially at the soil surface.

The objectives of this study were to (1) determine the effects of FA, applied at various rates, on the size distribution and stability of surface aggregates.

4.3.2 Materials and Methods

Please refer to Section 2.3.

4.3.3 Results and Discussion

Dry aggregate size distribution

The size distribution of dry aggregates at Site 1 was altered significantly due to the application of FA (Table 4.3a and Figure 4.4a). The percentage of aggregates > 6.3 mm in diameter was reduced from 50.1% of the total sample mass in the 0 Mg ha^{-1} rate of addition to 48.5, 44.2, 30.5 and 30.7% in the 6, 13, 26 and 53 Mg ha^{-1} treatments, respectively. This reduction in larger aggregates corresponded with an increase in aggregates in the 0.5 to 4.0 mm size range. This percentage increased from 32.6% in the 0 Mg ha^{-1} rate of FA addition to 34.7, 37.6, 49.8 and 49.1% in the 6, 13, 26 and 53 Mg ha^{-1} treatments, respectively. No significant differences in MWDs were found among the all rates of FA addition (Figure 4.6) at Site 1. However, MWD decreased from 6.52 mm in the 0 Mg ha^{-1} rate to 5.69, 5.77 and 5.22 mm for the 13, 26 and 53 Mg ha^{-1} FA applications rates, respectively.

Although the initial cloddiness at Site 2 was not as extensive as at Site 1, there was a similar effect on the dry aggregate size distribution (Table 4.3b and Figure 4.4b). The percentage of aggregates greater than 6.3 mm in diameter in the 0 Mg ha^{-1} treatment

was 34.1%. With the addition of FA at rates of 6, 13, 26 and 53 Mg ha^{-1}, the percentage of aggregates > 6.3 mm was 29.0, 24.1, 19.2 and 19.4% respectively. The drop in the number of aggregates > 6.3 mm corresponded with an increase in the amount of aggregates in the 0.5 to 4.0 mm size range; 43.6% in the Control and 47.3, 51.3, 55.7 and 57.5% in the 6, 13, 26 and 53 Mg ha^{-1} treatments, respectively. Along with the shift in aggregate size distribution due to the application of FA, so came a change in MWD. The application of FA at rates of 26 and 53 Mg ha^{-1} significantly decreased MWD (3.75 and 3.90 mm, respectively) at Site 2 compared to the 0 Mg ha^{-1} treatment (5.67 mm).

Of the three sites in this study, Site 3 had the best initial tilth, and was consequently influenced the least by the application of FA (Table 4.3c and Figure 4.4c). Still, the number of large aggregates > 6.3 mm decreased from 22.2% in the 0 Mg ha^{-1} rate to 15.3% for the 53 Mg ha^{-1} rate. No significant differences in MWD were observed among any of the rates of FA addition.

Wet aggregate stability

No significant changes in the size distribution of wet-sieved aggregates as a result of FA addition were observed in samples from Site 1 or 2 (Figure 4.5a and b). Some significant differences due to the application of FA in wet-sieved aggregate size distribution were observed at Site 3. The 6 Mg ha^{-1} application rate had a significantly higher percentage of aggregates in the 2-4 mm size range (11.1%) than did the 26 Mg ha^{-1} rate (8.2%). Aggregate size range for 6 and 26 Mg ha^{-1} rates were not significantly different from that for other rates of application .

Wet-sieve MWD at Site 1 was increased from 2.10 mm in the 0 Mg ha^{-1} rate to 2.45, 2.62, 2.29 and 2.21 mm in the 6, 13, 26 and 53 Mg ha^{-1} rates of application , respectively (Figure 4.7). This increase indicates greater stability of FA-amended soil under slaking conditions. Although there were no significant differences in wet-sieved MWD of the Site 2 samples, a slight decrease in MWD was observed with successively

higher rates of FA addition (Figure 4.7). Wet-sieve MWD decreased from 1.57 mm at the 0 Mg ha^{-1} rate to 1.40, 1.24, 1.13 and 1.04 mm in the 6, 13, 26 and 53 Mg ha^{-1} rates, respectively. No significant differences in the wet-sieve MWD due to FA addition were observed at Site 3.

In an effort to determine the difference in aggregate size from dry-sieved to wet-sieved conditions, the ratio of wet-sieve MWDs to dry-sieve MWDs were calculated: the MWD of water-sieved aggregates was divided by the MWD of dry-sieved aggregates and for each treatment, thus giving a ratio of wet MWD:dry MWD. The higher the wet MWD:dry MWD value obtained , the more stable the aggregates were under slaking conditions.

Significant differences in the wet MWD:dry MWD ratio as a result of FA addition were observed only in Site 1 (Figure 4.8). Relative size of the wet-sieve MWD increased significantly from 0.256 of the dry-sieve MWD to 0.512 in the 13 Mg ha^{-1} rate of FA addition. Although significant differences in the wet MWD:dry MWD ratio due to FA addition were not observed in the samples from Sites 2 and 3, aggregate stability increased with increasing rates of FA addition at Site 2 (Figure 4.8): the wet MWD:dry MWD ratio increased from 0.256 in the 0 Mg ha^{-1} rate to 0.309, 0.301, 0.351 and 0.382 in the 6, 13, 26 and 53 Mg ha^{-1} rates of FA application.

4.3.4 Conclusions

The addition of FA resulted in some significant changes in the size distribution of both dry-sieved and water-sieved aggregates. Significant changes due to FA addition occurred at the sites where initial soil tilth was the poorest, specifically, at Site 1. Wet aggregate stability, measured in the form of wet-sieve MWD and wet MWD:dry MWD ratios, was increased due to FA additions, but with no significant differences occurring between rates of FA application. No significant effects of FA addition on aggregate stability were observed (in terms of wet MWD:dry MWD), thus, rates of FA addition

higher than 53 Mg ha^{-1} may be needed in order to obtain siginificant results. Note however, these results were obtained only one year after application and longer term results yet have to be determined. FA addition of 26 Mg ha^{-1} or more could be recommended at Site 2 in order to decrease the size of aggregates for better seedbed quality, but according to wet MWD:dry MWD results, no significant decrease in soil erodibility to water would occur. Addition of FA would not have been needed at Site 3.

4.3.5 References

Hillel, D. 1982. Introduction to Soil Physics. Academic Press, Inc., San Diego, California. 364 pp.

Kemper, W.D. and Chepil, W.S. 1965. Size distribution of aggregates. In: C.A. Black (ed.), *Methods of Soil Analysis, Part 1.* Agronomy 9. American Society of Agronomy, Inc., Madison, Wisconsin, U.S.A. pp. 499-509.

Table 4.3a. Aggregate size distribution (w/w) of dry-sieved aggregates following application of fly ash at Site 1 measured on August 7, 1991.

Size range	Fly ash application rate (Mg ha^{-1})				
(mm)	0	6	13	26	53
< 0.125	0.009 a	0.007 a	0.010 a	0.012 a	0.016 a
0.125-0.25	0.011 b	0.009 b	0.014 ab	0.016 ab	0.020 a
0.25-0.5	0.029 b	0.028 b	0.036 ab	0.043 ab	0.049 a
0.5-1.0	0.070 a	0.074 a	0.088 a	0.112 a	0.122 a
1.0-2.0	0.111 b	0.123 ab	0.142 ab	0.191 a	0.182 ab
2.0-4.0	0.145 b	0.150 ab	0.146 ab	0.195 a	0.187 ab
4.0-6.3	0.124 a	0.124 a	0.121 a	0.127 a	0.117 a
6.3-9.5	0.118 a	0.120 a	0.108 a	0.110 a	0.102 a
9.5-12.5	0.094 a	0.098 a	0.086 a	0.077 a	0.071 a
12.5-25	0.173 a	0.192 a	0.174 a	0.109 a	0.111 a
> 25	0.116 a	0.075 a	0.074 a	0.009 a	0.023 a

Means in a row followed by a common letter are not significantly different at the 5 % level using the DMR test.

Table 4.3b. Aggregate size distribution (w/w) of dry-sieved aggregates following application of fly ash at Site 2 measured on August 7, 1991.

Size range	Fly ash application rate (Mg ha^{-1})				
(mm)	0	6	13	26	53
< 0.125	0.014 a	0.018 a	0.013 a	0.015 a	0.011 a
0.125-0.25	0.029 a	0.031 a	0.035 a	0.040 a	0.034 a
0.25-0.5	0.069 a	0.076 a	0.086 a	0.091 a	0.093 a
0.5-1.0	0.129 b	0.141 ab	0.159 ab	0.176 a	0.178 a
1.0-2.0	0.157 b	0.169 b	0.185 ab	0.213 a	0.218 a
2.0-4.0	0.150 a	0.163 a	0.169 a	0.168 a	0.179 a
4.0-6.3	0.110 a	0.112 a	0.112 a	0.103 ab	0.093 b
6.3-9.5	0.094 a	0.098 a	0.088 ab	0.072 b	0.069 b
9.5-12.5	0.070 a	0.066 a	0.068 a	0.053 a	0.051 a
12.5-25	0.148 a	0.088 ab	0.076 ab	0.057 b	0.068 b
> 25	0.029 a	0.038 a	0.009 a	0.010 a	0.006 a

Means in a row followed by a common letter are not significantly different at the 5 % level using the DMR test.

Table 4.3c Aggregate size distribution (w/w) of dry-sieved aggregates following application of fly ash at Site 3 measured on September 3, 1991.

Size range	Fly ash application rate (Mg ha^{-1})				
(mm)	0	6	13	26	53
< 0.125	0.050 b	0.058 ab	0.063 ab	0.061 ab	0.073 a
0.125-0.25	0.050 b	0.055 ab	0.060 ab	0.057 ab	0.063 a
0.25-0.5	0.111 a	0.116 a	0.127 a	0.118 a	0.130 a
0.5-1.0	0.159 a	0.163 a	0.073 a	0.162 a	0.176 a
1.0-2.0	0.170 a	0.176 a	0.182 a	0.175 a	0.176 a
2.0-4.0	0.150 a	0.151 a	0.149 a	0.152 a	0.142 a
4.0-6.3	0.088 a	0.094 a	0.090 a	0.093 a	0.086 a
6.3-9.5	0.077 a	0.073 ab	0.070 ab	0.069 ab	0.057 b
9.5-12.5	0.053 a	0.048 a	0.041 a	0.052 a	0.036 a
12.5-25	0.059 ab	0.065 a	0.038 b	0.047 ab	0.040 b
> 25	0.033 a	0.000 b	0.008 ab	0.012 ab	0.020 ab

Means in a row followed by a common letter are not significantly different at the 5 % level using the DMR test.

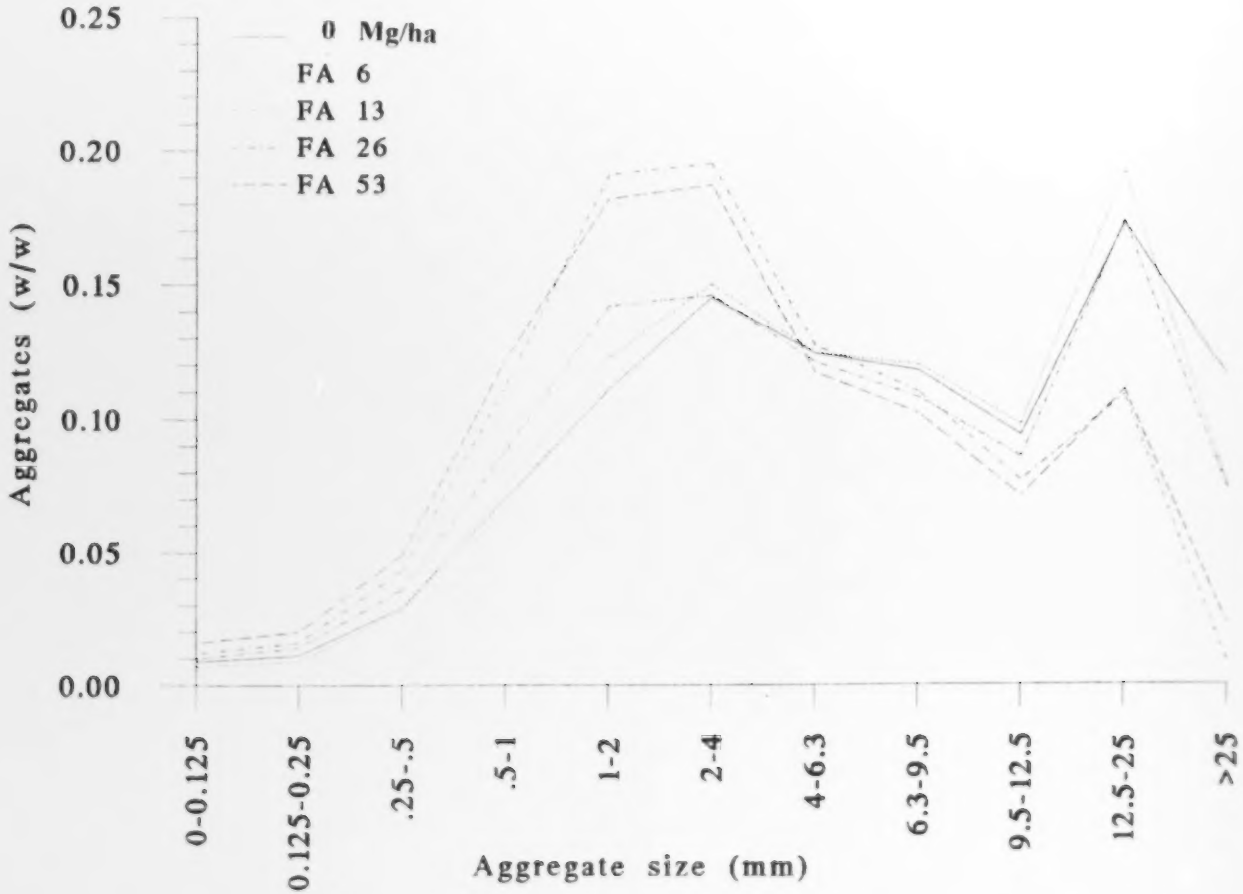

Figure 4.4a. Aggregate distribution after dry sieving of fly ash-amended soils at Site 1 on August 7, 1991.

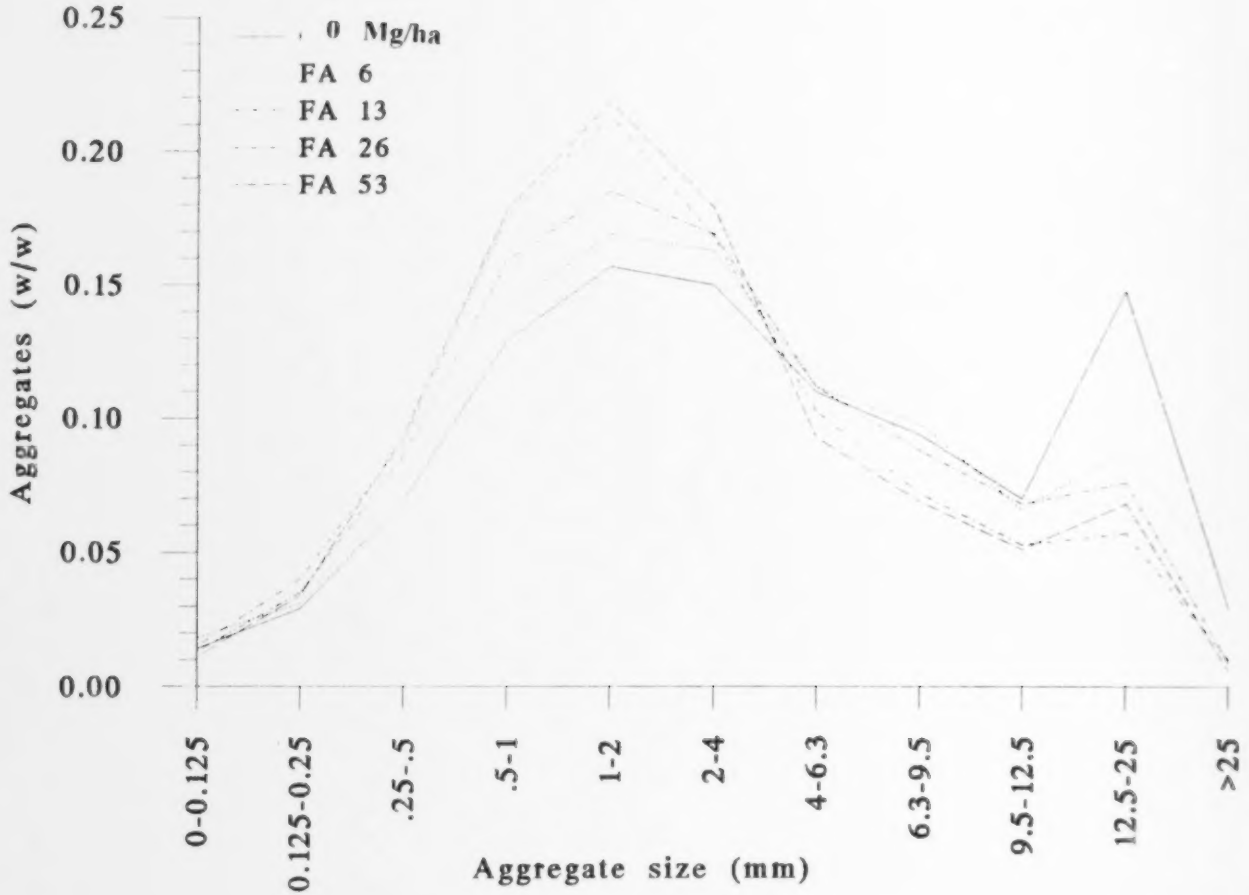

Figure 4.4b. Aggregate distribution after dry sieving of fly ash-amended soils at Site 2 on August 7, 1991

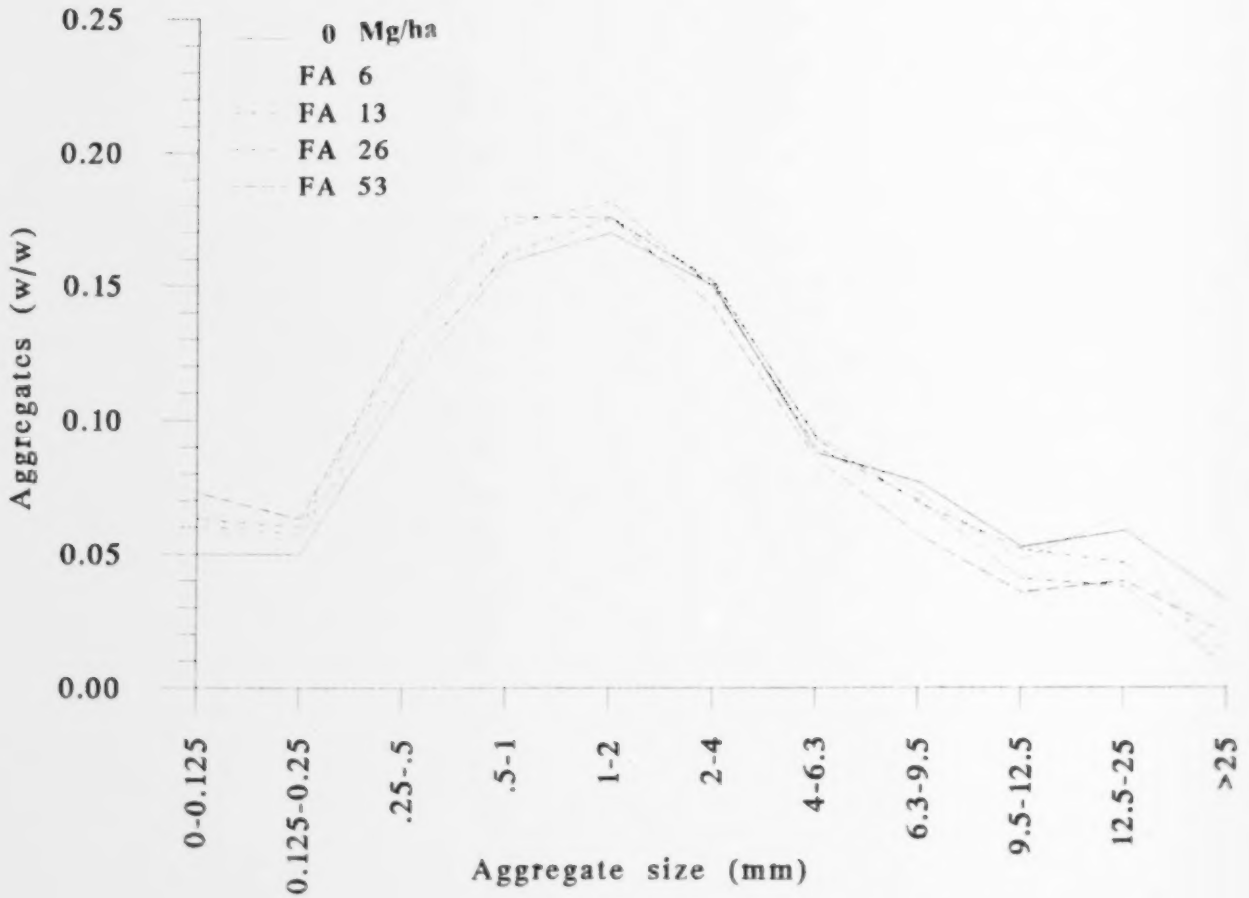

Figure 4.4c. Aggregate distribution after dry sieving of fly ash-amended soils at Site 3 on September 3, 1991.

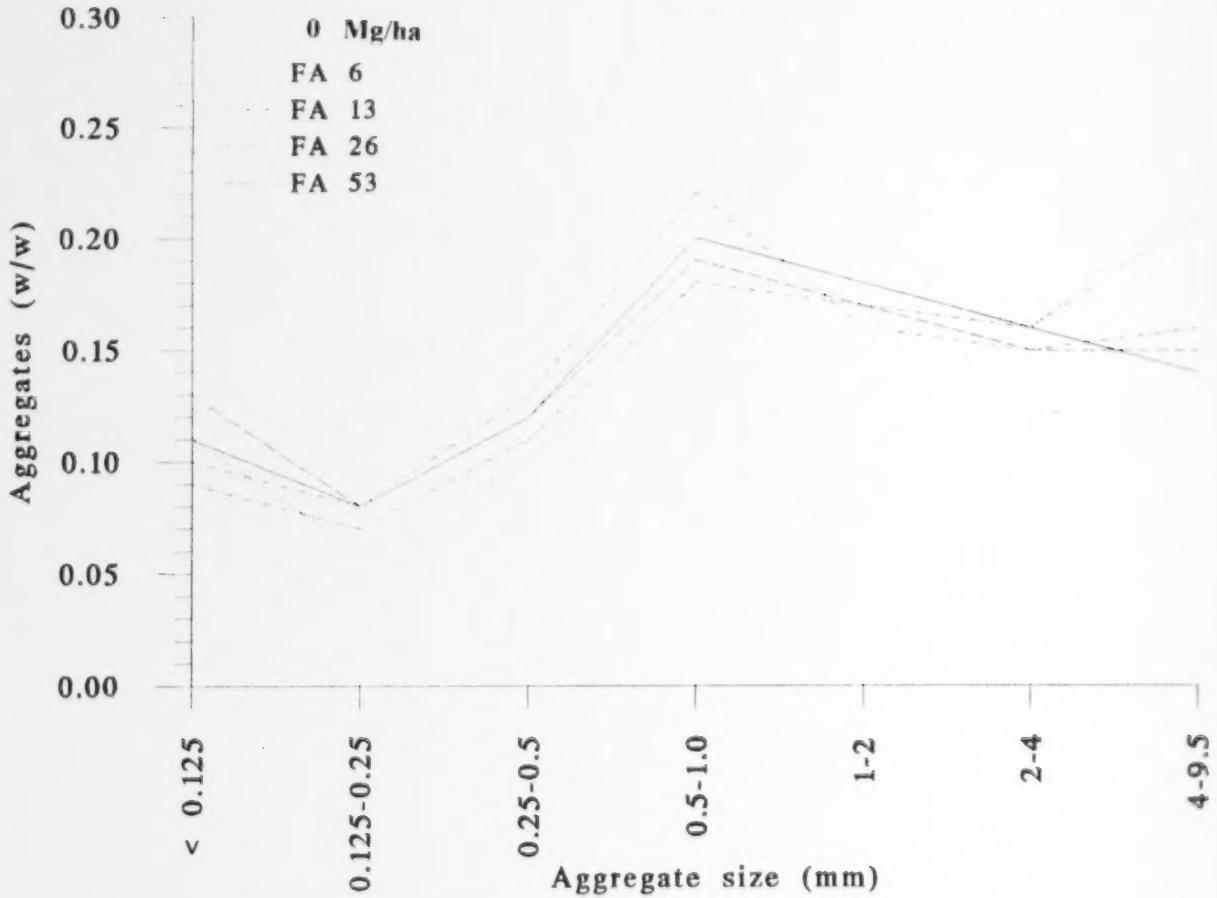

Figure 4.5a. Aggregate size distribution after wet-sieving of fly ash-amended soil at Site 1.

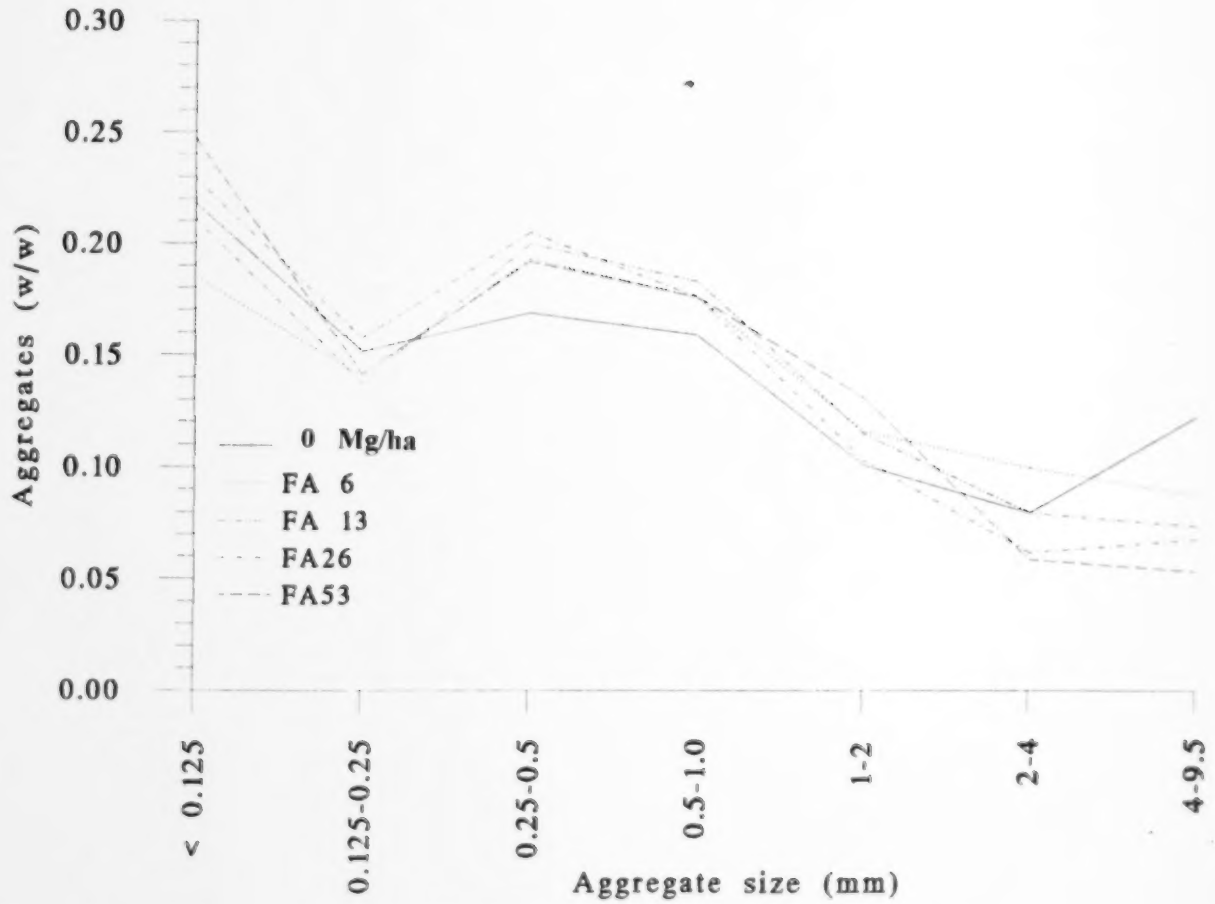

Figure 4.5b. Aggregate size distribution after wet-sieving of fly ash-amended soil at Site 2, October, 1991.

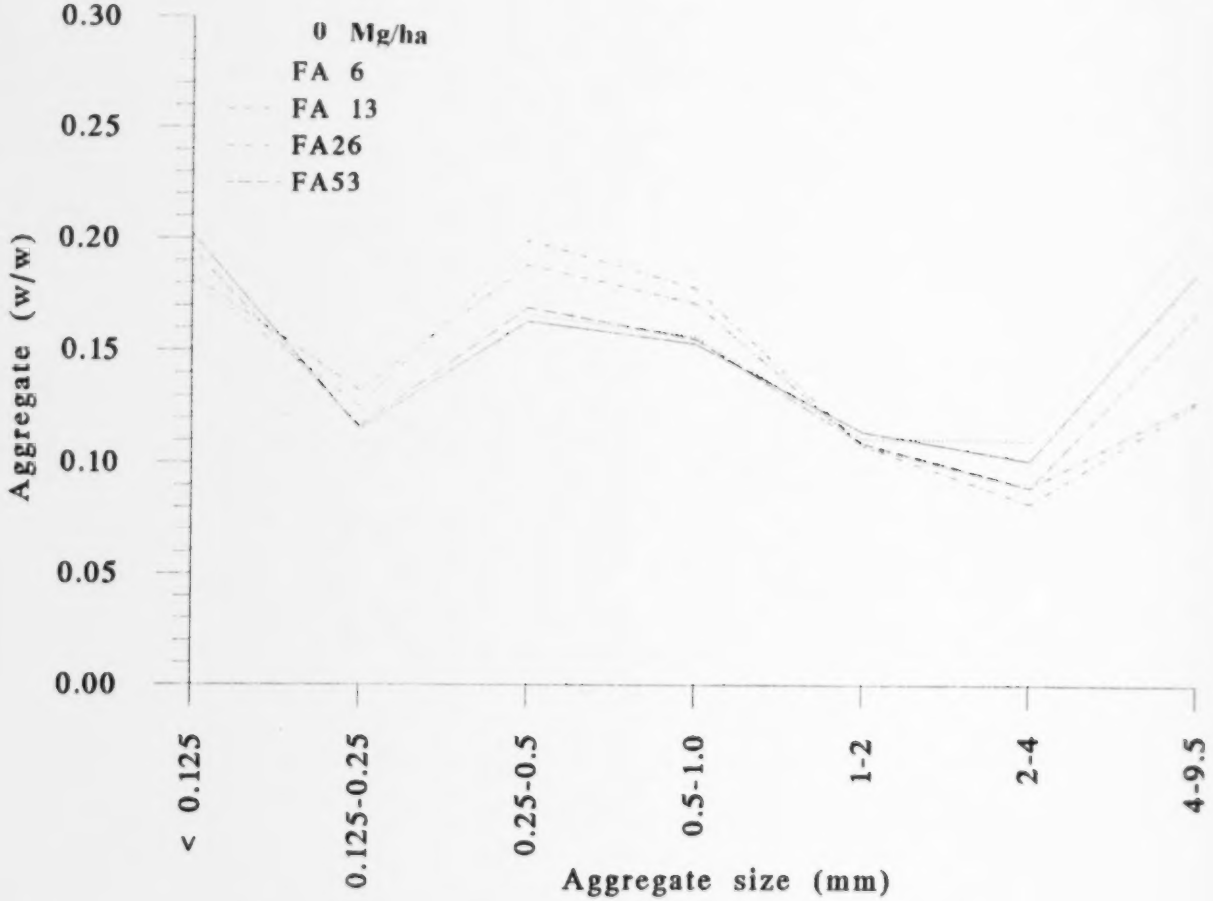

Figure 4.5c. Aggregate size distribution after wet-sieving of fly ash-amended soil at Site 3, October, 1991.

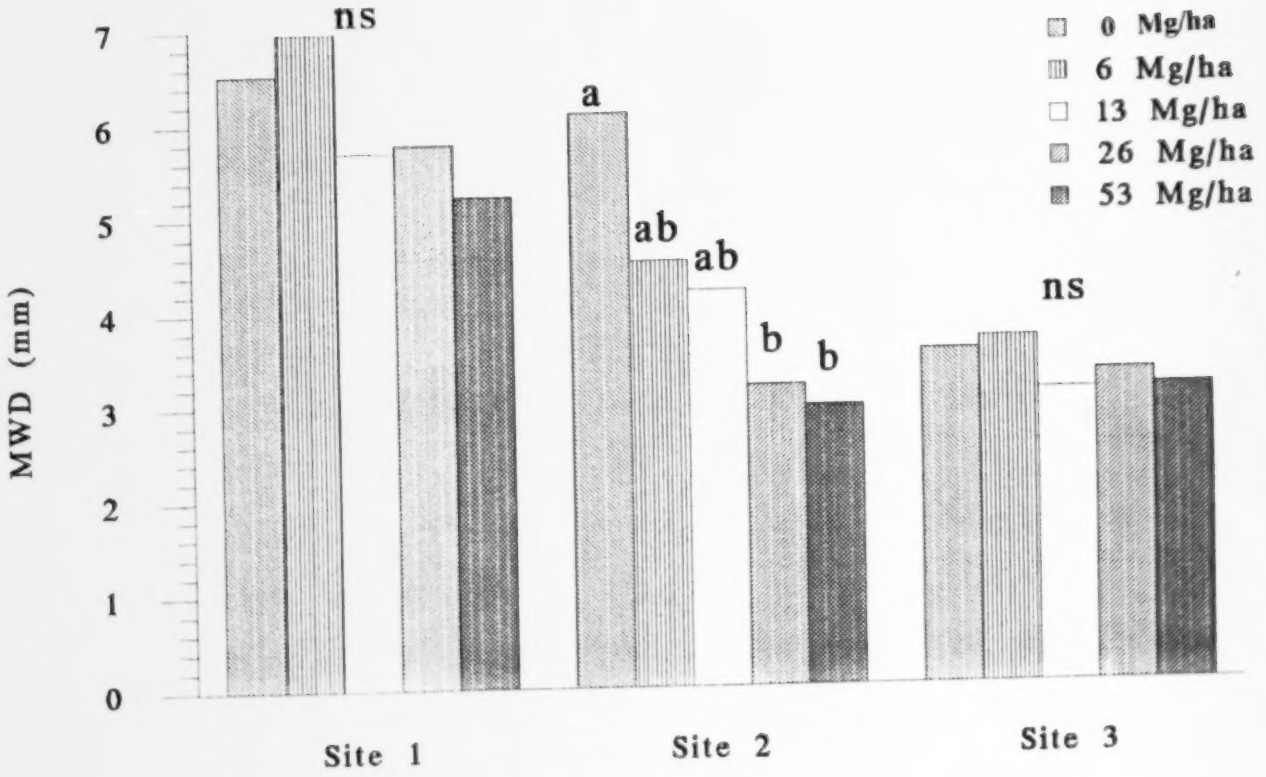

Figure 4.6 Mean weight diameters (MWD) of dry-sieved, FA-amended, soil at Sites 1, 2 and 3. Letters within each site indicate significant differences by Duncan's Multiple Range Test at the 5% level, ns=not significant.

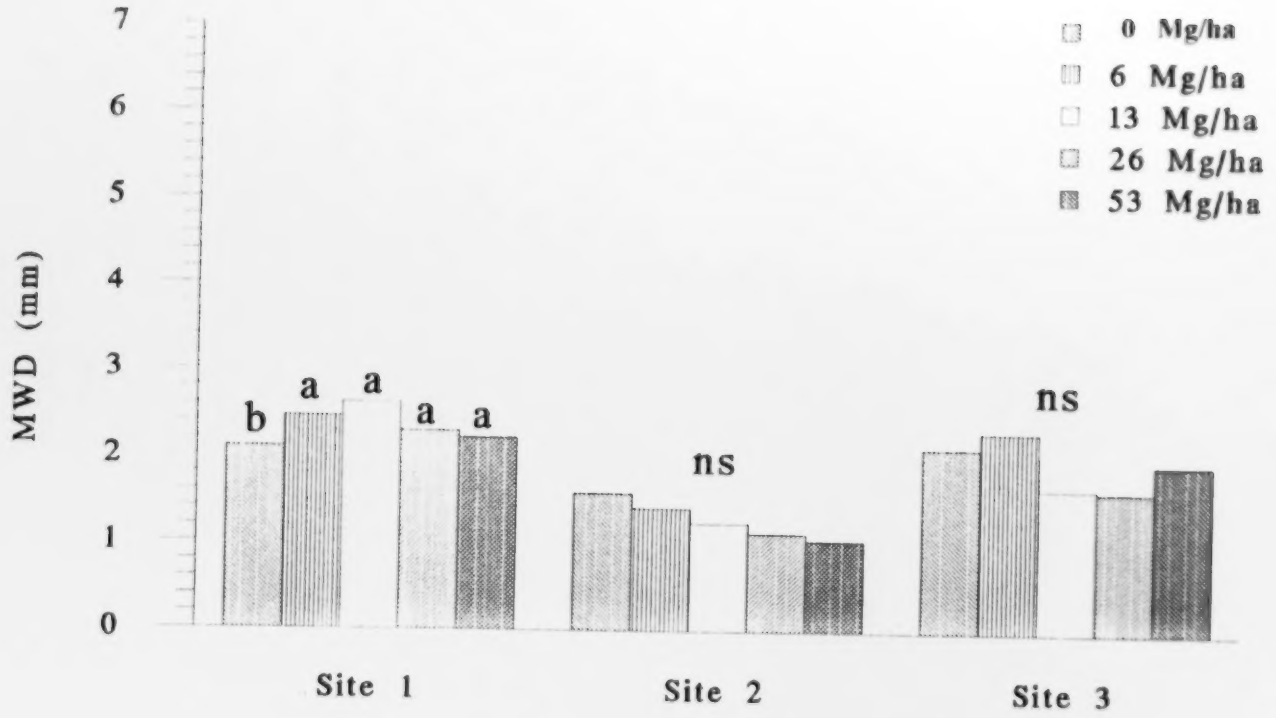

Figure 4.7 Mean weight diameters (MWD) of wet-sieved, FA-amended, soil at Sites 1, 2 and 3. Letters within each site indicate significant differences by Duncan's Multiple Range Test at the 5% level, ns=not significant.

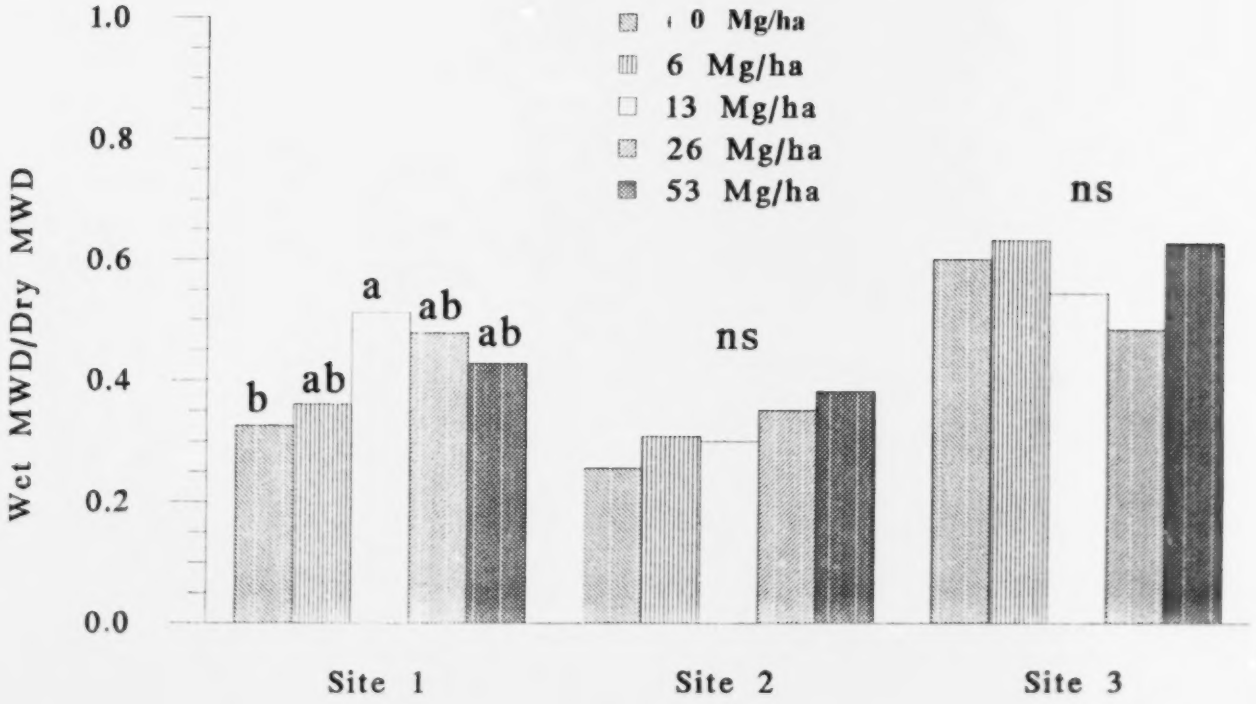

Figure 4.8 Ratio of wet-sieved MWD:dry-sieved MWD in FA-amended soil at Site 1, 2 and 3. Letters within each site indicate significant differences by Duncan's Multiple Range Test at the 5 % level, ns=not significant.

Chapter 5. Synthesis.

This study's main focus has been from a soil reclamation point of view with a goal of determining optimum rates of PG and FA addition to improve soil structure. All the recommended rates of application in the conclusions from previous sections (summarized in Table 5.1) were based on their beneficial effects on soil salinity/sodicity, pH and structure (i.e. tilth). Site 1 would require approximately 26 Mg ha^{-1} of PG with Site 2 requiring only 6 Mg ha^{-1} of PG in order to: reduce surface strength below 100 kPa, minimize aggregate size loss to 50 % and reduce the SAR to less than 2.3. Surface strength, change in aggregate size (wet MWD:dry MWD) and SAR results from the Control treatment at Site 3 were below the critical values previously mentioned, therefore, the addition of PG would not be required. Considering FA and using the criteria: Site 1 would require more than 53 Mg ha^{-1}, Site 2 would need 26-53 Mg ha^{-1}, and, for the same previously mentioned reasons, Site 3 would not need any FA.

Results from this study could be used to establish criteria to determine whether the addition of PG or FA would be beneficial in a given field situation. Criteria such as: surface strength (includes both modulus of rupture and in situ measurements), aggregate stability, EC and/or SAR could be used. Soil aggregate stability, modulus of rupture, EC and SAR determinations can be time consuming and require specialized, if not expensive, equipment. However, very similar results were obtained from the modulus of rupture and *in situ* measurement technique, therefore the *in situ* measurement could be a quick means by which to estimate surface crust strengths in the field. Both the modulus of rupture and *in situ* results correlated quite well with aggregate stability, EC and SAR results for PG, thus, determining crust strengths *in situ* may give a good indication of the aggregate stability, EC and/or SAR at the soil surface. This may also apply to other situations involving poor tilth; i.e. oil and gas lease sites, construction sites or agricultural soil with a high crusting potential.

Soils could be evaluated during the premining process in order to determine if there is a need for PG, FA or other amendments. For example, if a soil is sodic (such as the case at Site 1), the application of PG or FA before or during the stripping/stockpiling premining process may have given the reclamation process a head start. Sodicity is not as critical a factor at Site 2 as at Site 1. Because the soil at Site 2 may have been inherently low in organic matter (classified as a Dark Gray Luvisol), the addition of an organic matter-rich material, such as manure, could have been applied in conjunction with PG or FA during the reclamation process in order to improve soil tilth. Although the soil at Site 3, in its natural state, did not require the application of PG or FA, addition of either of these amendments during the premine process, especially to the Ap and Btgj horizons, may keep the clay flocculated while it is being stripped/stockpiled and subsequently reconstructed, thus helping the soil to retain some or all of its structural stability. In order to predetermine the amounts of PG or FA needed to improve soil tilth on a specific soil, soil-PG or soil-FA mixtures at various rates could be made in a laboratory. After the soil mixture has been subjected to extensive wet-dry cycles, MOR tests could be carried out to determine which rate would lower MOR to below 100 kPa. Although it requires more time and labour, aggregate size distributions after dry- and wet-sieving may also be carried out to determine which rates would be appropriate.

Addition of PG or FA could also be approached from a waste disposal point of view, where the object is to determine the maximum safe loading of either PG or FA on the soil. Maximum loading occurs when the rate of addition of PG or FA starts to affect the soil detrimentally. The 53 Mg ha^{-1} rate of PG or FA did not appear to have any detrimental influence on soil chemistry or soil tilth. Trends in some of the soil chemistry results indicate that additions of PG or FA at levels higher than 53 Mg ha^{-1} might be detrimental. Addition of PG at rates greater than 53 Mg ha^{-1} may increase EC to levels detrimental to plant growth. Soil salinity must also be taken into account if FA is applied at high rates, especially if unweathered ash is used. The effect of PG on soil pH must also

be taken into account, especially if inherent pH is already quite low. Acidic PG may lower soil pH to below inherent levels. No trends in soil structure/tilth within this study would prevent additions of PG or FA at levels beyond 53 Mg ha^{-1}. The effects of PG and FA on soil salinity and/or pH may be the main limitations to their addition at rates higher than those used in this study.

The recommendations in Table 5.1 are based on the assumption that there are no toxic or environmentally sensitive elements in PG or FA. Further research concerning the dissolution or release of such environmentally sensitive elements from PG or FA would have to be conducted before PG or FA could be routinely applied as a soil amendment.

Table 5.1 Recommendations for addition (Mg ha^{-1}) of phosphogypsum or fly ash at Sites 1, 2 and 3 for soil reclamation/improvement based on conclusions from previous sections.

		Amendment	
Parameter	Site	Phosphogypsum	Fly ash
Soil sodicity*	1	26	53+
	2	6	53+
	3	0	0
Soil pH	1	0	0
	2	0	26
	3	0	26
Surface strength**	1	26	53
	2	< 6	26
	3	0	0
Aggregate stability***	1	26	53+
	2	6	26
	3	0	0

* using SAR as indicator
** using MOR and in situ surface strength
*** using wet and dry sieving

6.0 Appendix

6.1 Chemistry data: means, maximums, minimums, standard deviations and coefficients of variances (CV). All samples for chemstry data obtained the first week of October 1991.

Table A1. Electrical conductivities of the 0-10 cm depth interval (dS m^{-1})

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
PG-amended soil at Site 1						
0	1.1	0.88	1.8	0.40	35	5
6	1.9	1.4	2.5	0.48	25	5
13	2.9	2.3	3.3	0.35	12	5
26	2.8	2.6	3.0	0.18	7	5
53	3.0	2.6	3.4	0.32	11	4
PG-amended soil at Site 2						
0	1.8	0.86	2.9	0.74	40	5
6	3.2	2.8	4.0	0.43	13	5
13	3.2	2.9	3.5	0.28	9	5
26	3.0	2.8	3.4	0.24	8	5
53	3.4	2.8	5.00	0.90	26	5
PG-amended soil at Site 3						
0	1.7	1.0	2.2	0.49	28	5
6	3.0	2.8	3.3	0.21	7	5
13	3.0	2.6	3.3	0.32	10	5
26	2.8	2.4	3.6	0.49	18	5
53	3.3	2.4	4.9	1.0	32	5
FA-amended soil at Site 1						
0	1.1	0.88	1.8	0.40	35	5
6	1.2	0.90	1.6	0.25	21	5
13	1.2	0.97	1.6	0.27	24	5
26	1.3	1.1	1.7	0.22	17	5
53	1.2	0.98	1.6	0.24	20	5
FA-amended soil at Site 2						
0	1.8	0.86	2.9	0.74	40	5
6	1.8	1.0	3.1	0.90	49	5
13	1.7	1.4	2.1	0.32	18	5
26	3.0	2.0	4.1	0.84	28	5
53	3.5	1.6	6.0	1.6	46	5
FA-amended soil at Site 3						
0	1.7	1.0	2.2	0.49	28	5
6	2.1	0.94	3.1	0.81	38	5
13	1.8	1.3	2.4	0.42	23	5
26	2.4	1.8	3.5	0.72	29	5
53	2.4	1.6	3.0	0.51	21	5

Table A2. Soluble cations and SAR of PG-amended soil (0-10 cm interval) at Site 1.

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Soluble Ca (mmol L^{-1})			
0	1.6	1.3	1.9	0.23	14	5
6	6.0	4.0	8.9	2.19	36	5
13	12	10	14	1.8	14	5
26	14	13	14	0.66	5	5
53	14	13	14	0.38	3	5
			Soluble Mg (mmol L^{-1})			
0	0.71	0.58	0.82	0.09	13	5
6	1.7	1.2	2.5	0.62	36	5
13	2.9	2.6	3.5	0.36	12	5
26	2.7	2.2	2.9	0.27	10	5
53	2.8	2.6	3.1	0.24	8	5
			Soluble Na (mmol L^{-1})			
0	9.1	6.7	16	4.2	46	5
6	10	6.9	13	2.3	23	5
13	10	7.7	15	3.2	30	5
26	9	7.2	12	1.8	20	5
53	11	8.7	13	1.8	16	5
			SAR			
0	6	4.0	11	2.7	45	5
6	3.7	3.0	4.4	0.64	17	5
13	2.7	1.8	4.1	0.89	33	5
26	2.2	1.7	2.9	0.49	22	5
53	2.7	2.1	3.3	0.47	17	5

Table A3. Soluble Cations and SAR of PG-amended soil (0-10 cm interval) at Site 2

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Soluble Ca (mmol L^{-1})			
0	4.4	1.8	6.6	1.9	43	5
6	13	12	14	0.85	6	5
13	14	14	16	1.0	7	5
26	15	13	15	0.73	5	5
53	16	14	21	3.0	20	5
			Soluble Mg (mmol L^{-1})			
0	2.2	1.0	3.2	0.80	37	5
6	4.6	4.2	5.1	0.33	7	5
13	4.5	4.2	4.8	0.22	5	5
26	4.2	3.4	4.7	0.54	13	5
53	5.0	4.0	7.8	1.6	32	5
			Soluble Na (mmol L^{-1})			
0	7.1	4.6	11	2.5	35	5
6	9.4	6.4	14	2.9	31	5
13	8.9	6.5	12	2.1	24	5
26	8.1	6.5	9.4	1.2	14	5
53	10	6.6	13	2.5	24	5
			SAR			
0	2.8	2.2	3.6	0.59	21	5
6	2.2	1.6	3.2	0.63	28	5
13	2.0	1.5	2.7	0.52	25	5
26	1.9	1.5	2.1	0.28	15	5
53	2.2	1.6	3.0	0.50	22	5

Table A4. Soluble Cations and SAR of PG-amended soil (0-10 cm interval)at Site 3.

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Soluble Ca (mmol L^{-1})			
0	6.1	3.6	8.5	2.0	33	5
6	16	16	18	0.98	6	5
13	17	16	18	1.0	6	5
26	16	15	18	1.6	10	5
53	14	2.6	20	6.7	48	5
			Soluble Mg (mmol L^{-1})			
0	2.5	1.8	3.3	0.64	25	5
6	4.1	3.8	4.3	0.21	5	5
13	3.9	3.3	4.4	0.48	12	5
26	4.0	3.3	4.6	0.46	12	5
53	4.6	3.3	7.4	1.64	36	5
			Soluble Na (mmol L^{-1})			
0	1.4	1.1	1.8	0.26	19	5
6	1.3	0.99	1.6	0.30	23	5
13	1.2	1.0	1.4	0.16	14	5
26	1.4	1.1	1.8	0.25	18	5
53	1.6	1.2	3.0	0.74	45	5
			SAR			
0	0.47	0.42	0.52	0.04	8	5
6	0.30	0.22	0.36	0.06	22	5
13	0.26	0.22	0.32	0.04	14	5
26	0.31	0.26	0.37	0.04	13	5
53	0.42	0.27	0.94	0.29	68	5

Table A5. Soluble Cations and SAR of FA-amended soil (0-10 cm interval) at Site 1.

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Soluble Ca (mmol L^{-1})			
0	1.6	1.3	1.9	0.23	14	5
6	2.2	1.6	3.1	0.55	25	5
13	2.1	1.5	3.1	0.58	28	5
26	2.3	1.9	2.6	0.37	16	5
53	2.3	1.8	2.8	0.37	16	5
			Soluble Mg (mmol L^{-1})			
0	0.71	0.58	0.82	0.09	13	5
6	0.89	0.66	1.1	0.18	21	5
13	0.90	0.70	1.2	0.23	25	5
26	0.82	0.78	0.86	0.03	4	5
53	0.81	0.66	0.90	0.11	13	5
			Soluble Na (mmol L^{-1})			
0	9.1	6.7	16	4.2	46	5
6	8.7	6.0	12	2.2	26	5
13	8.3	6.4	10	1.7	20	5
26	9.8	8.3	13	2.3	23	5
53	8.2	6.9	10	1.3	16	5
			SAR			
0	6.0	4.0	11	2.7	45	5
6	5.0	3.3	5.9	1.1	21	5
13	4.8	3.9	5.9	0.89	18	5
26	5.5	4.6	7.0	1.1	20	5
53	4.6	4.1	5.5	0.53	11	5

Table A6. Soluble Cations and SAR of FA-amended soil (0-10 cm interval) at Site 2.

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Soluble Ca (mmol L^{-1})			
0	4.4	1.8	6.6	1.9	43	5
6	5.2	2.6	9.4	3.0	57	5
13	4.8	3.6	5.9	1.1	22	5
26	10	5.5	14	3.3	32	5
53	13	4.8	23	6.8	54	5
			Soluble Mg (mmol L^{-1})			
0	2.2	1.0	3.2	0.80	37	5
6	2.4	1.4	4.1	1.2	50	5
13	2.2	1.6	2.7	0.43	20	5
26	3.8	2.5	4.8	1.0	26	5
53	4.3	4.8	8.2	2.4	55	5
			Soluble Na (mmol L^{-1})			
0	7.1	4.6	11	2.5	35	5
6	7.1	5.0	8.8	1.7	24	5
13	6.9	5.2	8.4	1.3	19	5
26	8.7	6.2	13	2.8	32	5
53	11	6.7	17	4.4	41	5
			SAR			
0	2.8	2.2	3.6	0.59	21	5
6	2.7	4.5	3.3	0.34	13	5
13	2.6	1.9	3.0	0.43	16	5
26	2.3	1.8	3.1	0.55	24	5
53	2.6	1.8	3.2	0.54	20	5

Table A7. Soluble Cations and SAR of FA-amended soil (0-10 cm interval) at Site 3.

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Soluble Ca (mmol L^{-1})			
0	6.1	3.6	8.5	2.0	33	5
6	8.2	3.4	13	3.3	40	5
13	6.5	4.3	9.1	1.8	27	5
26	9.4	6.7	14	3.1	33	5
53	9.7	6.6	12	2.0	21	5
			Soluble Mg (mmol L^{-1})			
0	2.5	1.8	3.3	0.64	25	5
6	3.0	1.5	4.4	1.1	35	5
13	2.4	1.8	3.3	0.56	23	5
26	3.2	2.4	4.6	0.91	28	5
53	2.9	2.1	3.7	0.59	20	5
			Soluble Na (mmol L^{-1})			
0	1.4	1.1	1.8	0.26	19	5
6	1.4	0.26	2.4	0.79	55	5
13	1.5	1.2	1.6	0.12	9	5
26	2.0	1.6	2.7	0.48	23	5
53	1.8	1.4	2.6	0.44	24	5
			SAR			
0	0.47	0.42	0.52	0.04	8	5
6	0.44	0.08	0.59	0.21	49	5
13	0.50	0.43	0.53	0.04	8	5
26	0.58	0.42	0.72	0.13	22	5
53	0.51	0.43	0.65	0.08	16	5

6.2 Surface strength data: means, maximums, minimums, standard deviations. coefficients of variance and sample sizes.

Table A8. Mean ISSs of PG-amended soil at Site 1 (kPa).

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			August 19, 1991 sampling date			
0	150	41	358	85	57	25
6	92	34	165	41	44	25
13	77	34	200	36	47	25
26	59	14	103	17	29	25
53	68	28	110	20	29	25
			September 3, 1991 sampling date			
0	241	124	448	91	38	25
6	134	83	193	26	20	25
13	118	14	172	33	28	25
26	109	48	200	38	35	25
53	77	34	103	19	25	25
			September 25, 1991 sampling date			
0	167	69	400	102	61	25
6	74	41	103	18	24	25
13	56	14	83	20	36	25
26	53	28	83	16	29	25
53	65	28	83	14	21	25
			Mean ISS over all sampling dates			
0	186	94	395	86	46	25
6	100	74	140	19	19	25
13	84	46	122	19	23	25
26	74	41	110	17	23	25
53	70	53	97	12	17	25

Table A9. Mean ISSs of PG-amended soil at Site 2 (kPa).

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			September 10, 1991 sampling date			
0	134	103	179	17	13	25
6	74	34	131	22	30	25
13	80	28	124	33	41	25
26	72	28	124	26	36	25
53	76	34	124	29	38	25
			September 25, 1991 sampling date			
0	117	69	193	27	23	25
6	92	55	138	26	28	25
13	80	41	117	21	26	25
26	86	34	117	22	25	25
53	94	55	145	28	30	25
			Mean ISS over all sampling dates			
0	126	100	172	17	14	25
6	83	59	107	14	17	25
13	80	48	117	21	26	25
26	79	52	107	15	19	25
53	85	52	121	20	24	25

Table A10. Mean ISSs of PG-amended soil at Site 3 (kPa).

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			September 10, 1991 sampling date			
0	78	34	124	24	30	25
6	42	21	76	14	33	25
13	53	21	83	17	32	25
26	52	21	103	21	40	25
53	63	28	103	19	31	25
			September 25, 1991 sampling date			
0	96	41	145	23	24	25
6	65	34	103	20	31	25
13	68	41	96	16	24	25
26	70	34	103	18	26	25
53	68	41	90	15	22	25
			Mean ISS over all sampling dates			
0	87	59	117	14	16	25
6	54	31	86	15	28	25
13	60	41	90	11	19	25
26	61	41	90	14	22	25
53	66	41	83	11	17	25

Table A11. Mean ISSs of FA-amended soil at Site 1 (kPa).

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
August 19, 1991 sampling date						
0	150	41	358	85	57	25
6	86	28	172	35	41	25
13	109	34	193	44	40	25
26	98	55	213	37	38	25
53	98	28	207	36	37	25
September 3, 1991 sampling date						
0	241	124	448	91	38	25
6	182	103	331	62	34	25
13	173	103	289	61	35	25
26	142	83	262	37	26	25
53	118	69	172	24	20	25
September 25, 1991 sampling date						
0	167	69	400	102	61	25
6	92	41	193	44	47	25
13	86	48	152	30	35	25
26	83	41	124	22	27	25
53	71	34	145	36	51	25
Mean ISS over all sampling dates						
0	186	94	395	86	46	25
6	120	69	209	36	31	25
13	123	74	198	31	25	25
26	108	78	177	23	21	25
53	96	55	138	19	20	25

Table A12. Mean ISSs of FA-amended soil at Site 2.

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			September 10, 1991 sampling date			
0	134	103	179	17	13	25
6	85	55	131	22	26	25
13	92	28	165	37	41	25
26	79	48	110	21	26	25
53	95	55	138	23	24	25
			September 25, 1991 sampling date			
0	117	69	193	27	23	25
6	127	55	193	33	26	25
13	108	55	172	36	33	25
26	107	48	172	30	29	25
53	112	41	200	42	38	25
			Mean ISS over all sampling dates			
0	126	100	172	17	14	25
6	106	62	145	18	17	25
13	100	55	145	27	27	25
26	93	59	117	16	17	25
53	104	55	165	28	27	25

Table A13. Mean ISSs of FA-amended soil at Site 3.

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			September 10, 1991 sampling date			
0	78	34	124	24	30	25
6	67	41	110	23	35	25
13	54	34	103	18	34	25
26	65	41	103	20	30	25
53	73	41	124	20	28	25
			September 25, 1991 sampling date			
0	96	41	145	23	24	25
6	81	55	110	16	20	25
13	72	34	138	24	33	25
26	77	48	110	16	21	25
53	66	34	96	20	31	25
			Mean ISS over all sampling dates			
0	87	59	117	14	16	25
6	74	52	107	14	19	25
13	63	41	93	14	23	25
26	71	48	86	11	15	25
53	69	52	96	11	16	25

Table A14. Mean Modulus of Rupture (kPa) of the 0-10 cm depth interval.

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			PG-amended soil at Site 1			
0	255	96	538	109	43	23
6	214	50	495	116	54	24
13	107	31	320	80	75	25
26	60	19	167	39	65	25
53	41	16	73	18	43	24
			PG-amended soil at Site 2			
0	95	49	142	27	28	25
6	82	27	138	34	41	23
13	71	38	173	39	55	22
26	70	28	120	23	33	24
53	55	21	153	34	61	24
			PG-amended soil at Site 3			
0	74	52	98	14	18	25
6	80	56	105	15	18	25
13	62	41	98	16	26	25
26	60	34	90	17	29	25
53	55	31	70	10	19	25
			FA-amended soil at Site 1			
0	255	96	538	109	43	23
6	325	131	668	156	48	25
13	161	37	346	86	53	23
26	176	27	389	134	76	25
53	79	22	181	43	54	24
			FA-amended soil at Site 2			
0	95	49	142	27	28	25
6	71	27	176	41	58	25
13	94	38	206	45	48	25
26	53	28	120	24	45	22
53	55	22	144	37	68	25
			FA-amended soil at Site 3			
0	74	52	98	14	18	25
6	71	32	111	22	31	25
13	48	31	66	10	20	25
26	67	48	89	10	14	25
53	43	27	58	9	22	25

6.3 Mean weight diameter data: means, minimums, maximums, standard deviations, coefficients of variance and sample sizes. Samples for dry sieving were obtained August 7, 1991 and samples for wet sieving on October 4, 1991.

Table A15. Mean weight diameters (MWD) of PG-amended soil at Site 1 (0-10 cm)

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Dry-sieved MWD			
0	6.5	5.5	7.7	0.90	14	5
6	6.4	5.0	9.2	1.7	27	5
13	5.1	4.0	7.3	1.4	27	5
26	3.9	3.2	4.8	0.63	16	5
53	4.0	3.3	4.7	0.60	15	5
			Wet-sieved MWD			
0	2.1	1.8	2.5	0.32	15	5
6	2.4	1.9	3.5	0.62	26	5
13	2.0	1.5	2.2	0.30	15	5
26	1.9	1.7	2.2	0.20	10	5
53	2.8	2.4	3.4	0.39	14	5
			Wet-sieved MWD:Dry-sieved MWD			
0	0.32	0.26	0.38	0.047	0.14	5
6	0.39	0.21	0.51	0.12	30	5
13	0.41	0.29	0.54	0.90	22	5
26	0.51	0.40	0.67	0.10	20	5
53	0.73	0.58	0.80	0.087	0.12	5

Table A16. Mean weight diameters (MWD) of PG-amended soil at Site 2 (0-10 cm).

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Dry-sieved MWD			
0	5.6	4.3	7.3	1.2	20	5
6	3.6	2.5	5.1	1.1	29	5
13	3.3	3.0	3.7	0.30	9	5
26	3.6	2.6	5.2	0.97	27	5
53	3.6	2.7	5.2	1.0	28	5
			Wet-sieved MWD			
0	1.6	0.93	2.2	0.63	40	3
6	1.4	1.2	1.7	0.26	18	3
13	1.3	0.91	1.6	0.37	28	3
26	1.5	1.2	1.8	0.31	20	3
53	1.3	1.3	1.4	0.055	4	3
			Wet-sieved MWD:Dry-sieved MWD			
0	0.26	0.19	0.36	0.090	35	3
6	0.47	0.26	0.70	0.22	46	3
13	0.42	0.24	0.51	0.15	36	3
26	0.44	0.36	0.55	0.099	23	3
53	0.44	0.37	0.47	0.058	13	3

Table A17. Mean weight diameters (MWD) of PG-amended soil at Site 3 (0-10 cm).

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Dry-sieved MWD			
0	3.6	3.5	3.8	0.13	4	5
6	3.3	2.8	3.9	0.41	12	5
13	2.7	2.5	2.9	0.41	12	5
26	2.5	2.0	3.2	0.46	18	5
53	2.3	2.0	2.9	0.36	16	5
			Wet-sieved MWD			
0	2.1	1.7	2.6	0.46	21	3
6	2.0	1.6	3.0	0.77	38	3
13	1.5	1.1	1.9	0.41	27	3
26	1.7	1.5	1.8	0.15	9	3
53	1.9	1.8	2.0	0.12	6	3
			Wet-sieved MWD:Dry-sieved MWD			
0	0.60	0.48	0.75	0.13	22	3
6	0.58	0.46	0.76	0.16	28	3
13	0.55	0.40	0.67	0.14	25	3
26	0.75	0.60	0.92	0.16	22	3
53	0.90	0.90	0.91	0.0072	1	3

Table A18. Mean weight diameters (MWD) of FA-amended soil at Site 1 (0-10 cm).

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Dry-sieved MWD			
0	6.5	5.5	7.7	0.90	14	5
6	7.0	5.0	8.2	1.4	20	5
13	5.7	3.3	7.8	1.6	29	5
26	5.4	3.3	8.4	2.1	39	5
53	5.2	4.5	6.5	0.84	16	5
			Wet-sieved MWD			
0	2.1	1.8	2.5	0.32	15	5
6	2.4	1.7	3.2	0.52	21	5
13	2.6	2.0	3.0	0.40	15	5
26	2.3	1.8	2.5	0.28	12	5
53	2.2	1.6	2.4	0.32	14	5
			Wet-sieved MWD:Dry-sieved MWD			
0	0.32	0.26	0.38	0.047	0.14	5
6	0.36	0.28	0.49	0.10	26	5
13	0.51	0.32	0.90	0.24	46	5
26	0.48	0.28	0.66	0.18	38	5
53	0.43	0.35	0.49	0.065	15	5

Table A19. Mean weight diameters (MWD) of FA-amended soil at Site 2 (0-10 cm)

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Dry-sieved MWD			
0	5.6	4.3	7.3	1.2	20	5
6	4.6	3.7	5.8	0.92	20	5
13	4.4	3.0	5.4	0.94	22	5
26	3.8	2.8	5.5	1.0	28	5
53	3.9	2.4	6.0	1.4	37	5
			Wet-sieved MWD			
0	1.6	0.93	2.2	0.63	40	3
6	1.4	1.2	1.8	0.39	28	3
13	1.2	1.1	1.4	0.15	12	3
26	1.1	0.83	1.6	0.39	35	3
53	1.0	0.72	1.5	0.43	41	3
			Wet-sieved MWD:Dry-sieved MWD			
0	0.26	0.19	0.36	0.090	35	3
6	0.31	0.24	0.36	0.064	21	3
13	0.30	0.27	0.36	0.047	16	3
26	0..35	0.26	0.44	0.092	26	3
53	0.38	0.20	0.65	0.23	61	3

Table A20. Mean weight diameters (MWD) of FA-amended soil at Site 3 (0-10 cm)

Rate of addition (Mg ha^{-1})	Mean	Minimum	Maximum	Standard Deviation	CV (%)	N
			Dry-sieved MWD			
0	3.6	3.5	3.8	0.13	4	5
6	3.7	3.1	4.4	0.49	13	5
13	3.1	2.5	3.5	0.43	14	5
26	3.4	2.8	4.2	0.59	17	5
53	2.9	2.2	4.0	0.70	24	5
			Wet-sieved MWD			
0	2.1	1.72	2.6	0.45	21	3
6	2.3	2.2	2.4	0.064	3	3
13	1.6	1.5	1.8	0.14	8	3
26	1.6	0.98	2.2	0.62	38	3
53	1.9	1.5	2.3	0.42	22	3
			Wet-sieved MWD:Dry-sieved MWD			
0	0.60	0.48	0.75	0.13	22	3
6	0.63	0.56	0.67	0.066	10	3
13	0.54	0.44	0.66	0.11	21	3
26	0.48	0.34	0.60	0.13	27	3
53	0.63	0.53	0.78	0.13	21	3

6.4 ANOVA tables: Soil chemistry data of the 0-10 cm depth interval at Sites 1, 2 and 3.

Table A20. ANOVA tables for EC data.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		PG-amended soil at Site 1			
Block	4	0.94	0.24	1.8	0.18
Application rate	4	12	2.9	23	0.0001
Error	16	1.9	0.13		
Total	24	15			
		PG-amended soil at Site 2			
Block	4	2.1	0.53	1.8	0.17
Application rate	4	7.9	2.0	6.9	0.0020
Error	15	4.6	0.29		
Total	23	15			
		PG-amended soil at Site 3			
Block	4	1.4	0.35	1.0	0.42
Application rate	4	7.2	1.8	5.3	0.0063
Error	16	5.4	0.34		
Total	24	14			
		FA-amended soil at Site 1			
Block	4	0.35	0.087	1.1	0.38
Application rate	4	0.11	0.027	0.35	0.84
Error	16	1.2	0.078		
Total	24	1.7			
		FA-amended soil at Site 2			
Block	4	5.3	1.3	1.5	0.24
Application rate	4	14	3.4	3.9	0.021
Error	16	14	0.86		
Total	24	33			
		FA-amended soil at Site 3			
Block	4	0.48	0.12	0.28	0.89
Application rate	4	2.3	0.56	1.3	0.31
Error	16	6.9	0.43		
Total	24	9.6			

Table A21. ANOVA tables for soluble cation data of PG-amended soil at Site 1.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		Soluble Ca			
Block	4	8.5	2.1	1.3	0.31
Application rate	4	598	150	91	.0001
Error	16	26	1.6		
Total	24	633			
		Soluble Mg			
Block	4	0.48	0.12	0.92	0.47
Application rate	4	17.5	4.4	33	0.0001
Error	16	2.1	0.13		
Total	23	20			
		Soluble Na			
Block	4	42	10	1.4	0.27
Application rate	4	18	4.5	0.61	0.66
Error	16	117	7.3		
Total	24	176			
		SAR			
Block	4	12	2.9	2.0	0.15
Application rate	4	44	11	7.5	0.0013
Error	16	24	1.5		
Total	24	80			

Table A22. ANOVA tables for soluble cation data of PG-amended soil at Site 2.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		Soluble Ca			
Block	4	8.0	2.0	0.61	0.66
Application rate	4	420	105	32	0.0001
Error	16	50	3.3		
Total	24	480			
		Soluble Mg			
Block	4	2.6	0.65	0.86	0.51
Application rate	4	25	6.2	8.2	0.0009
Error	16	12	0.76		
Total	23	40			
		Soluble Na			
Block	4	50	12	3.5	0.0319
Application rate	4	27	6.8	1.9	0.16
Error	16	59	3.6		
Total	24	136			
		SAR			
Block	4	1.7	0.42	1.8	0.18
Application rate	4	2.5	0.63	2.7	0.066
Error	16	3.7	0.23		
Total	24	7.8			

Table A23. ANOVA tables for soluble cation data of PG-amended soil at Site 3.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		Soluble Ca			
Block	4	32	7.9	0.69	0.61
Application rate	4	400	100	8.7	0.0006
Error	16	180	11		
Total	24	610			
		Soluble Mg			
Block	4	4.4	1.1	1.8	0.18
Application rate	4	12	2.9	4.8	0.010
Error	16	9.9	0.62		
Total	23	26			
		Soluble Na			
Block	4	1.0	0.25	1.9	0.16
Application rate	4	0.57	0.14	1.1	0.41
Error	16	2.1	0.13		
Total	24	3.7			
		SAR			
Block	4	0.092	0.023	1.33	0.30
Application rate	4	0.16	0.040	2.3	0.10
Error	16	0.28	0.017		
Total	24	0.52			

Table A24. ANOVA tables for soluble cation data of FA-amended soil at Site 1.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		Soluble Ca			
Block	4	1.0	0.26	1.4	0.30
Application rate	4	1.7	0.42	2.2	0.12
Error	15	2.8	0.19		
Total	23	5.5			
		Soluble Mg			
Block	4	0.19	0.047	2.9	0.058
Application rate	4	0.12	0.029	1.82	0.18
Error	15	0.24	0.016		
Total	23	0.55			
		Soluble Na			
Block	4	22	5.4	0.79	0.55
Application rate	4	5.2	1.3	0.19	0.94
Error	15	100	6.8		
Total	23	130			
		SAR			
Block	4	7.7	1.9	0.86	0.51
Application rate	4	5.6	1.4	0.63	0.65
Error	15	34	2.2		
Total	23	56			

Table A25. ANOVA tables for soluble cation data of FA-amended soil at Site 2.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		Soluble Ca			
Block	4	79	20	1.56	0.23
Application rate	4	280	71	5.57	0.0053
Error	15	200	13		
Total	23	560			
		Soluble Mg			
Block	4	9.0	2.2	1.35	0.29
Application rate	4	21	5.2	3.14	0.044
Error	15	27	1.7		
Total	23	56			
		Soluble Na			
Block	4	47	12	1.79	0.18
Application rate	4	54	14	2.0	0.14
Error	15	100	6.6		
Total	23	210			
		SAR			
Block	4	0.89	0.22	0.87	0.50
Application rate	4	0.64	0.16	0.63	0.65
Error	15	4.1	0.26		
Total	23	5.6			

Table A26. ANOVA tables for soluble cation data of FA-amended soil at Site 3.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		Soluble Ca			
Block	4	9.0	2.2	0.30	0.87
Application rate	4	55	14	1.8	0.17
Error	16	120	7.4		
Total	24	180			
		Soluble Mg			
Block	4	0.76	0.19	0.27	0.89
Application rate	4	2.2	0.54	0.77	0.56
Error	16	11	0.70		
Total	23	14			
		Soluble Na			
Block	4	0.88	0.22	0.97	0.45
Application rate	4	1.7	0.43	1.9	0.16
Error	16	3.6	0.23		
Total	24	6.2			
		SAR			
Block	4	0.037	0.0094	0.59	0.67
Application rate	4	0.059	0.15	0.94	0.47
Error	16	0.25	0.016		
Total	24	0.35			

6.5 ANOVA tables for surface strength data at Sites 1, 2 and 3.

Table A27. ANOVA tables of ISS for PG-amended soil at Site 1.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		August 19, 1991 sampling date			
Block	4	4800	1200	0.64	0.64
Application rate	4	26000	6500	3.4	0.034
Error	16	30000	1900		
Total	24	61000			
		September 3, 1991 sampling date			
Block	4	6000	1500	0.76	0.56
Application rate	4	78000	19000	9.8	0.0003
Error	16	32000	2000		
Total	23	120000			
		September 25, 1991 sampling date			
Block	4	13000	3300	1.4	0.27
Application rate	4	45000	11000	5.0	0.0085
Error	16	36000	2300		
Total	24	95000			

Table A28. ANOVA tables of ISS for PG-amended soil at Site 2.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		September 10, 1991 sampling date			
Block	4	3300	820	2.2	0.13
Application rate	4	14000	3400	9.2	0.0005
Error	16	5900	370		
Total	24	23000			
		September 25, 1991 sampling date			
Block	4	1200	300	1.4	0.27
Application rate	4	4100	1000	4.8	0.0094
Error	16	3400	210		
Total	23	8700			

Table A29. ANOVA tables of ISS for PG-amended soil at Site 3.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		September 10, 1991 sampling date			
Block	4	1300	320	2.0	0.14
Application rate	4	3700	920	5.6	0.0050
Error	16	2600	160		
Total	24	7500			
		September 25, 1991 sampling date			
Block	4	700	170	1.4	0.27
Application rate	4	3100	780	6.4	0.0029
Error	16	1900	120		
Total	23	5800			

Table A30. ANOVA tables of ISS for FA-amended soil at Site 1.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		August 19, 1991 sampling date			
Block	4	13000	3200	2.2	0.12
Application rate	4	12000	3100	2.1	0.13
Error	16	24000	1500		
Total	24	49000			
		September 3, 1991 sampling date			
Block	4	11000	2600	0.85	0.51
Application rate	4	43000	11000	3.4	0.033
Error	16	50000	3100		
Total	23	104000			
		September 25, 1991 sampling date			
Block	4	24000	6000	2.4	0.090
Application rate	4	29000	7300	2.9	0.054
Error	16	40000	2500		
Total	24	93000			

Table A31. ANOVA tables of ISS for FA-amended soil at Site 2.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		September 10, 1991 sampling date			
Block	4	2500	640	2.2	0.12
Application rate	4	9100	2300	7.8	0.0011
Error	16	4700	290		
Total	24	16000			
		September 25, 1991 sampling date			
Block	4	1100	280	0.34	0.84
Application rate	4	1400	350	0.43	0.78
Error	16	13000	810		
Total	23	15000			

Table A32. ANOVA tables of ISS for FA-amended soil at Site 3.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		September 10, 1991 sampling date			
Block	4	2400	610	4.7	0.011
Application rate	4	1700	420	3.2	0.040
Error	16	2100	130		
Total	24	6200			
		September 25, 1991 sampling date			
Block	4	1000	250	1.3	0.31
Application rate	4	2600	660	3.3	0.037
Error	16	3200	200		
Total	23	6800			

Table A33. ANOVA tables for modulus of rupture (MOR) data.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		PG-amended soil at Site 1			
Block	4	21000	5300	0.84	0.52
Application rate	4	180000	45000	7.2	0.0016
Error	16	100000	6300		
Total	24	300000			
		PG-amended soil at Site 2			
Block	4	6700	1700	3.4	0.035
Application rate	4	4300	1100	2.2	0.12
Error	15	7900	500		
Total	23	19000			
		PG-amended soil at Site 3			
Block	4	340	80	0.39	0.81
Application rate	4	2200	560	2.6	0.078
Error	16	3400	220		
Total	24	6000			
		FA-amended soil at Site 1			
Block	4	41000	10000	1.0	0.42
Application rate	4	180000	44000	4.4	0.014
Error	16	190000	10000		
Total	24	380000			
		FA-amended soil at Site 2			
Block	4	7600	1900	2.4	0.088
Application rate	4	8200	2000	2.6	0.073
Error	16	12000	770		
Total	24	28000			
		FA-amended soil at Site 3			
Block	4	870	220	1.4	0.29
Application rate	4	3900	980	6.1	0.0035
Error	16	2600	160		
Total	24	7300			

6.6 ANOVA tables for mean weight diameter (MWD) data.

Table 34. ANOVA tables for mean weight diameters (MWD) at Site 1.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
PG-amended. Dry-sieved MWD					
Block	4	3.8	0.96	0.72	0.59
Application rate	4	32	8.1	6.0	0.0037
Error	16	22	1.3		
Total	24	58			
PG-amended. Wet-sieved MWD					
Block	4	0.36	0.090	0.53	0.72
Application rate	4	2.8	0.69	4.1	0.018
Error	15	2.7	0.17		
Total	23	5.8			
PG-amended. Wet MWD/Dry MWD					
Block	4	0.014	0.0035	0.36	0.83
Application rate	4	0.49	0.12	0.13	0.0001
Error	16	0.16	0.0097		
Total	24	0.66			
FA-amended. Dry-sieved MWD					
Block	4	9.0	2.2	1.1	0.40
Application rate	4	11	2.8	1.4	0.29
Error	16	33	2.1		
Total	24	54			
FA-amended. Wet-sieved MWD					
Block	4	0.63	0.16	1.1	0.38
Application rate	4	0.85	0.21	1.5	0.24
Error	16	2.2	0.14		
Total	24	3.7			
FA-amended. Wet MWD/Dry MWD					
Block	4	0.17	0.043	2.7	0.067
Application rate	4	0.12	0.03	2.0	0.15
Error	16	0.25	0.016		
Total	24	0.54			

Table 35. ANOVA tables for mean weight diameters (MWD) at Site 2.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
		PG-amended, Dry-sieved MWD			
Block	4	5.1	1.3	1.6	0.23
Application rate	4	18	4.4	5.5	
Error	16	13	0.81		
Total	24	36			
		PG-amended, Wet-sieved MWD			
Block	2	0.45	0.22	1.9	0.21
Application rate	4	0.16	0.039	0.33	0.85
Error	8	0.96	0.12		
Total	14	1.6			
		PG-amended, Wet MWD/Dry MWD			
Block	2	0.10	0.052	5.1	0.038
Application rate	4	0.088	0.022	2.2	0.16
Error	8	0.080	0.010		
Total	14	0.27			
		FA-amended, Dry-sieved MWD			
Block	4	3.9	0.98	0.75	0.57
Application rate	4	11	2.8	2.1	0.13
Error	16	21	1.3		
Total	24	36			
		FA-amended, Wet-sieved MWD			
Block	2	0.37	0.19	1.0	0.40
Application rate	4	0.53	0.13	0.73	0.59
Error	8	1.4	0.18		
Total	14	2.4			
		FA-amended, Wet MWD/Dry MWD			
Block	2	0.045	0.022	1.6	0.26
Application rate	4	0.028	0.0071	0.51	0.073
Error	8	0.11	0.014		
Total	14	0.18			

Table 35. ANOVA tables for mean weight diameters (MWD) at Site 3.

Source	Degrees of freedom	Sum of squares	Mean sum of squares	F	Pr>F
PG-amended, Dry-sieved MWD					
Block	4	0.22	0.055	0.42	0.79
Application rate	4	6.2	1.5	12	0.0001
Error	16	2.1	0.13		
Total	24	8.4			
PG-amended, Wet-sieved MWD					
Block	2	1.1	0.55	4.9	0.041
Application rate	4	0.81	0.20	1.8	0.22
Error	8	0.89	0.11		
Total	14	2.8			
PG-amended, Wet MWD/Dry MWD					
Block	2	0.070	0.035	2.5	0.14
Application rate	4	0.27	0.07	4.8	0.028
Error	8	0.11	0.014		
Total	14	0.45			
FA-amended, Dry-sieved MWD					
Block	4	0.52	0.13	0.45	0.77
Application rate	4	2.3	0.57	2.0	0.14
Error	16	4.6	0.29		
Total	24	7.4			
FA-amended, Wet-sieved MWD					
Block	2	0.32	0.16	1.0	0.40
Application rate	4	1.0	0.26	1.7	0.25
Error	8	1.2	0.16		
Total	14	2.6			
FA-amended, Wet MWD/Dry MWD					
Block	2	0.025	0.012	0.88	0.45
Application rate	4	0.048	0.012	0.84	0.53
Error	8	0.11	0.014		
Total	14	0.19			